ENERGY MEASURES ACROSS HOCKEY HELMET IMPACT LOCATIONS

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This study examined the relationship between risk of head injury and energy loading across hockey helmet impact locations as another measure to assess helmet performance in reducing the risk of head injuries. A medium size NOCSAE headform instrumented with linear accelerometers was used to simulate dynamic impacts to the head during a free fall. The measured impact force was then used to determine energy loading and severity index. The results indicated that the energy loading on the helmet material accounts for 11.56% of the variance in predicting the risk of head injury across hockey helmet impact locations. This information becomes useful for researchers, coaches and helmet designers to better understand the material properties of helmets in energy loading and the role that the geometry of the helmet plays in minimizing the risk of traumatic brain injuries due to impact.

KEYWORDS: Concussion, Hockey Helmet Testing, Energy Loading, Peak Linear Acceleration

INTRODUCTION: Concussions or mild traumatic brain injuries occur due to biomechanical forces impacting the head causing an alteration in brain function (Menon, Schwab, Wright, & Maas, 2010). In the sport of ice hockey, helmets represent the best form of head protection against concussions (Post, Oeur, Hoshizaki, & Gilchrist, 2011). The capability of hockey helmets to mitigate the risk of concussions during an impact can be assessed, for example, using a pass or fail criterion with a threshold peak linear acceleration value ranging from 275 to 300 g's during a free-fall protocol (Post, Oeur, Hoshizaki, & Gilchrist, 2011). The pass-or-fail criterion is simple to apply but does not take into account factors such as rotational accelerations, shear forces, energy unloading and energy dissipation. This creates the need to explore other measurement techniques to better understand the material properties of hockey helmets to load and unload the energy generated due to a head impact. This energy represents the work performed to deform the helmet lining material and to restore it to its original shape when a head collision occurs. According to the law of conservation of energy, the absorbed mechanical energy does not remain in the helmet, but converts into another form of energy such as heat, and dissipates overtime (Zumdahl & Zumdahl, 2010). Researchers examined this type of energy analysis technique on bicycle helmets and soccer headgear (Marsh, McPherson, & Zerpa, 2008; Monthatipkul, Iovenitti, & Sbarski, 2012). Current hockey helmet testing standards, however, do not include analyses or protocols focusing on the energy loaded onto the head, which primarily gets absorbed through the attenuation liner or foam layer (Cui, Kiernan, & Gilchrist, 2009). In addition, current helmet testing protocols do not examine the extent to which energy measures predict the risk of head injury due to a head impact. Therefore, the purpose of this study was to examine the relationship between the risk of head injury and energy loading due to a head impact across helmet locations.

METHODS: A medium size National Operating Committee on Standards for Athletic Equipment (NOCSAE) headform instrumented with linear accelerometers was used to simulate dynamic impacts to the head during a free fall. The NOCSAE headform was attached to a mechanical neckform made out of neoprene rubber with steel end plates to emulate a human neck. The researchers set the strength of the neck by adjusting the stiffness of the mechanical neck with a torque of 1.35 N-m. The mechanical neckform, together with a drop carriage, was let fall freely in a dual rail drop system. The masses of the headform, neckform, helmet and drop carriage added up to 10 kg and remained the same for the entire data collection process. A 110-volt AC winch with a wire connected to a magnetic plate elevated the drop assembly (of headform, neckform, helmet and drop carriage) to the correct height prior to each impact. When the magnetic plate was energized, it grabbed the assembly. With the press of a release switch on the electronic controller, the magnets were de-energized and the assembly fell freely on the impact anvil surface. The anvil impact surface was mounted on a rubber matting bolted into the floor to minimize noise and vibration caused during impact. The helmet was tested by dropping it across five (5) helmet locations including the front, front boss, rear, rear boss and side. To minimize wear and tear of the helmet material, identical helmets were alternately used after each impact to allow ample time for the impacted helmet to rebound to its resting state. Each location got impacted 18 times with impact velocities ranging from 2.6 to 4.5 m/s. For each impact, the accelerometer sensors captured the linear acceleration data (x, y, and z directions) and an AMTI force platform captured the impact forces (x, y and z directions). The accelerometer and force signals were fed into an analog to digital amplifier unit and the information was processed via a PowerLab AD Instruments software to compute the resultant acceleration and force. A data sampling frequency of 20,000 Hz was set for each acceleration or force input channel. A low pass SAE j211 filter with a cut-off frequency of 1000 Hz eliminated the noise generated due to vibrations induced to the headform during the free falls. Impact locations were tested in a sequential order, ensuring that all impacts to helmets at a given location were completed before moving to the next location. A total of 270 impacts were conducted (3 identical helmets × 18 speeds × 5 impact locations). Next, energy loading was computed using the force platform measures and Equation 1. The NOCSAE Severity Index (SI) was computed using Equation 2 to determine the risk of injury for each impact during the testing protocol. This Severity Index (SI) uses linear impact accelerations and it cannot exceed a value of 1200, which represents an acceptable level according to NOCSAE helmet testing standards (NOCSAE, 2014).

$$E_{Loading} = \int_0^S F ds \tag{1}$$

where:

$E_{Loading}$ = energy produced due to the deformation of material shape at impact
F = (resultant) force to deform the material shape at impact
ds = compression interval
S = total displacement of material due to deformation

$$SI = \int_{t_0}^{t_1} A^{2.5} dt \tag{2}$$

where:

SI = injury severity index due to a head impact
A = head acceleration impulse function
t_1 = impulse duration

Finally, a Pearson’s product-moment correlation and linear regression analysis was conducted to examine the degree of relationship between energy loading and Severity Index.

RESULTS: As can be seen in Table 1, of all impact locations, the front boss location produced the highest liner impact acceleration and the highest Severity Index or risk of head injury. On the contrary, the rear boss location produced the lowest linear impact acceleration and the lowest risk of head injury. In terms of energy loading on the helmet material, the front location generated the highest amount and the side location the least when comparing all helmet impact locations.

Table 1: Mean Values and Standard Deviations (in Parentheses) of Measures of Linear Impact Acceleration, Severity Index and Energy Loading

Neck Torque (N-m)	Location	Peak Linear Acceleration (g)	Severity Index (SI)	Energy Loading (J)
1.35	Front	137.65 (38.35)	610.28 (311.21)	150.05 (34.12)
	Rear	120.28 (29.56)	452.66 (226.24)	124.99 (40.72)
	Side	118.23 (30.71)	405.64 (205.47)	107.34 (30.65)
	Front Boss	146.61 (56.43)	612.59 (390.92)	128.12 (16.19)
	Rear Boss	109.79 (35.58)	383.34 (207.14)	132.49 (36.34)

When analysing the strength of the linear relationship between impact energy loading and injury Severity Index, the Pearson's product-moment correlation indicated a statistically significant moderate correlation between these two dependent variables, r = .340, p < .05. Based on this finding, a linear model to predict the Severity Index or risk of head injury based on the energy loaded onto the system was suggested as shown in Equation 3.

$$\mathrm{SI} = 1.9404 * \mathrm{E_{Loading}} + 184.9 \quad (3)$$

where:

$E_{Loading}$ = Energy loaded onto the system
SI = Severity Index

The slope of the equation indicates that for every increase of 1 J in energy loaded onto the system, the risk of injury or Severity Index increases by 1.9404 SI.

DISCUSSION: Equation (3) presents a simple approach to estimate the injury risk based on the amount of energy loaded onto the system. This model, however, only accounts for 11.56% of the variance given by the strength of the relationship between energy loading and Severity Index, which leaves 88.44% of the variance unexplained. This unexplained variance may be due to other factors such as neck strength, rotational accelerations, shear forces, energy unloading and energy dissipation that were not accounted for in this model. The scatter plot of ($E_{Loading}$, SI) shows a wide scattering of data points within the range of $E_{Loading}$ = 100 – 150 J. Other relationships than the linear one should be investigated in the future.

The present study aimed to examine the extent to which energy loading across helmet impact locations predicts the risk of head injury. As stated in the literature, more advanced methods need to be developed to better examine the protective ability of hockey helmets to optimize injury risk reduction due to a head impact (O'Brien & Meehan, 2015). Current methods such as the SI estimate the risk of head injury due to an impact by including measures of linear acceleration and time (NOCSAE, 2014; O'Brien & Meehan, 2015; Oukama, 2013; Rousseau & Hoshizaki, 2009). This technique, however, does not take into account the material properties of the helmet to reduce risk of head injury based on the force applied and the deformation of the helmet material expressed as energy loading, which seems to account for 11.56% in predicting risk of head injury in the current study. As stated by Ghajari and Galvanetto (2013), current testing methods focusing on peak linear acceleration should be improved by including other measures such as force and energy to provide better guidelines for helmet designers and therefore, possibly reduce the occurrence of injuries. The outcome of the present data also indicates that the energy loading seems to differ across helmet impact locations. This difference may be related to the helmet geometry across locations, consequently affecting the risk of head injury. While measures of energy loading seem to be promising in predicting risk of head injury, there is still an 88.44% of variance unaccounted for in the current study. Future research should include other predictors in the model such as helmet locations, angles of impact, shear forces, angular accelerations, energy unloading, energy dissipation and neck strength to examine the weight of these predictors in estimating the risk of injury, and more specifically the risk of concussions in the sport of ice hockey.

A limitation of the current study includes the use of only one type of helmets, although tens of identical helmets were impacted during the study. The use of one type of helmets makes it difficult to generalize the outcome to other helmet types. The methodology, however, will be used in later research studies with different types of hockey helmets.

CONCLUSION: This study sheds light on the use of energy loading measures as a possible predictor of risk of head injury. The study also highlights the need to examine other predictors to account for the unpredicted variance of the current regression model. The outcome of this study and future research may have implications for researchers, helmet designers and hockey players to better understand the effect of other factors besides linear accelerations to reduce the risk of head injury and possibly concussions.

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