THE EFFECT OF ANGLE OF IMPACT, NECK STIFFNESS, AND IMPACT LOCATION ON MEASURES OF SHEAR FORCES DURING HELMET TESTING

Carlos Zerpa[1], Stephen Carlson[1], Paolo Sanzo[1],

Eryk Przysucha[1], Thomas Hoshizaki[1], Derek Kivi[1]

Lakehead University, School of Kinesiology, Thunder Bay, Canada[1]

The purpose of this study was to examine the effect of angle of impact, neck stiffness, and impact location on measures of shear forces during a fall ground head collision to better understand the protective ability of a hockey helmet. Eighteen impacts at different velocities were conducted on 5 helmet impact locations, under 3 neck stiffness settings and 2 impact angles. Shear forces were measured for a total of 540 helmet impacts. A three way factorial ANOVA revealed a significant three-way interaction effect between impact location, neck stiffness and angle of impact on shear force measures, $F(8, 510)= 5.550$, $p<.005$, $\eta^2= .080$. The outcome of this study suggests that neck strength and angle of impact combined influence the magnitude of the shear forces responsible for generating angular accelerations across helmet impact locations during a fall ground head collision. The outcome of this study highlight the need to develop helmet testing protocols to better understand the ability of helmets to protect the head against shear forces during an impact.

KEY WORDS: Shear force, neck stiffness, helmet impact location

INTRODUCTION: Hockey is a fast and aggressive sport with a large potential for injury (Flik, Lyman, & Marx, 2005). The inherent risk of injury has led to the development of helmets as protective devices to minimize linear accelerations and the transference of forces to the head. (Kis et al., 2013; Wennberg & Tator, 2003). Helmet testing is usually conducted by mounting the helmet on a surrogate “headform”, designed to respond closely to an actual human head. Accelerometers instrumented in the headform measure the linear accelerations felt by the headform during an impact (Post et al., 2011). The maximum threshold value accepted for peak linear impact acceleration ranges from 275 to 300gs. This range was obtained from human cadaver research conducted on skull fractures (Gurdjian, Roberts, & Thomas, 1966). The unit “g” is used for any linear acceleration analysis and is simply a multiple of the acceleration due to gravity ($g=9.81\ m/s^2$). If the peak linear acceleration measured during the impact is less than the threshold acceleration range, the helmet is deemed appropriately protective. While this measure of peak linear acceleration is based on the acceleration experienced by the brain through the centre of mass, along the plane of impact, this testing method may not be indicative of the rigor of the sport of hockey. Current research in hockey helmet testing has also determined that rotational accelerations expressed in radians per seconds contribute to the occurrence of concussion and diffuse axonal injuries in the brain (King et al., 2003). These rotational accelerations are caused in part by shear forces applied to the head during impact (Kleiven, 2013) but are not generally included in initial helmet testing protocols. The relationship between angle of impact and acceleration measures during hockey helmet impact testing has also been studied in the past (Walsh, Rousseau, & Hoshizaki, 2011; Zhang, Yang, & King, 2011), however, the effect of the angle of impact and neck stiffness on shear forces have not yet been studied extensively in helmet design and performance across impact locations of the helmet. Based on this rationale, the purpose of this study was to examine the effect of neck stiffness, impact location, and angle of impact on measures of shear forces during a fall ground head collision to better understand the protective ability of a hockey helmet.

METHODS: A NOCSAE headform designed by Hodgson (1975) to simulate the dynamic response that a human head experiences during impacts was used for this study. The headform was mounted on a mechanical neckform. The neckform was attached to a drop carriage and it was used to simulate the dynamic response of a human neck during impacts.

The drop carriage was mounted on a frictionless railing system which behaved as free falling. The weight of the headform, neck, and drop carriage was 30.6 kg and remained the same throughout the testing protocol. A 110-volts AC winch with a wire connected to a magnetic plate controlled by an electronic unit was used to elevate the drop carriage to the correct height to obtain the appropriate drop velocities ranging from 2.62 m/s to 4.85 m/s prior to each impact. Upon release, a switch was pressed on the electronic unit and the drop carriage freely dropped on an angle bracket set on top of an Advanced Mechanical Technology Incorporated (AMTI) force platform to measure shear forces for each impact. The angle bracket was set on top of the force platform at 0 and 13.5 degrees as depicted in Figure 1.

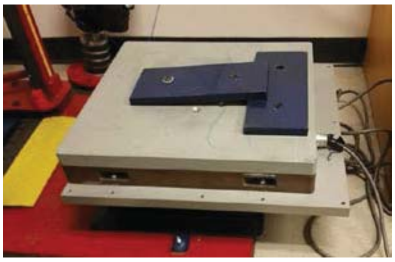

Figure 1: Platform with angle bracket at the base of impact.

Identical hockey helmets were used during the testing. Each helmet was properly fitted on the headform prior to each drop by following helmet fitting instructions as defined by NOCSAE standards (NOCSAE, 2014). Based on data obtained from a wear and tear test and analysis, each helmet was changed after 90 impacts to protect the integrity of the data. The order of impacts was as follows: front, front boss, side, rear boss, and rear as defined by NOCSAE standards. Each helmet was subjected to 1 impact for each combination of neck stiffness, angle, and location. The neckform stiffness was adjusted to analyze the influence of neck compliance characteristics on dynamic response. Similar to the protocol by Rousseau and Hoshizaki (2009), neck compliance was adjusted to 30% above and below the standard neckform stiffness setting (e.g., 30% below '8.4 in-lb', standard '12in-lb', 30% above '15.6 in-lb'). Eighteen selected drop heights ranging from 0.35 m to 1.20 m were used to obtain the appropriate drop velocities, from 2.62 m/s to 4.85 m/s, similar to the research protocol of Marsh et al. (2004). The 18 different drop velocities were completed on a combination of 5 impact locations of a helmet, 3 neck stiffness settings, and 2 impact angles for a total of 540 helmet impacts. For each impact, the shear force measures captured by the AMTI force platform were fed into an analog to digital amplifier unit and processed via a commercial software package called POWERLAB. The data was collected at a sampling rate of 20,000 Hz. To analyze the data, a three way factorial ANOVA was used to examine the interaction effects of 5 impact locations, 3 neck stiffness settings, and 2 impact angles on measures of shear impact force during the fall head collision. Statistical significance was test at $p< 0.05$.

RESULTS: The three-way factorial ANOVA, revealed a significant three-way interaction effect between the independent variables on shear force, $F(8, 510)=5.550$, $p<.005$, $\eta^2=.080$. To help explain the interaction, a simple two way analysis of variance was conducted and the results revealed an interaction effect between helmet impact location and neck stiffness on shear force for each impact angle, 0 degree $F(8, 510)=4.337$, $p<.005$, $\eta^2= .064$ and 13.5 degrees, $F(8, 510)=2.019$, $p=.043$, $\eta^2=.031$ as depicted in Figure 2 and Figure 3.

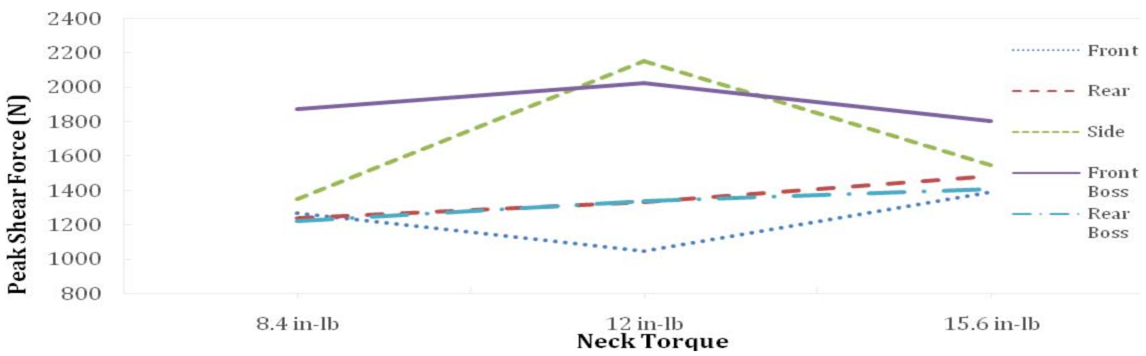

Figure 2: Neck torque and impact location interaction on peak shear force for the 0 degree angle.

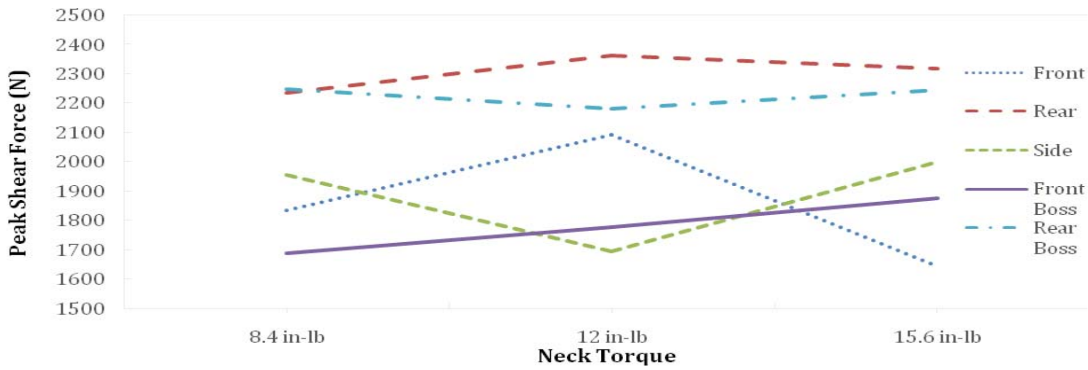

Figure 3: Neck torque and impact location interaction on peak shear force for the 13.5 degree angle.

DISCUSSION: The purpose of this study was to examine the effect of neck stiffness, helmet impact location and angle of impact on shear force measures to better understand the protective ability of a helmet material in distributing these forces. The results of the current study revealed that neck stiffness, impact angle, and location of impact seemed to influence the ability of the helmet to distribute shear forces. As depicted in Figure 1 for the zero impact angle, the front and rear boss locations generated lower shear forces across neck torques than the other helmet locations, indicating that the front and rear boss locations managed the distribution of shear forces more effectively during a direct impact. Rousseau and Hoshizaki (2009), found a similar effect when manipulating neckform stiffness for direct projectile impacts. When increasing the angle of impact to 13.5 degrees to generate a diffuse impact, the shear forces as depicted in Figure 2 increased for each location across neck torques. In particular, the rear and rear boss locations behaved differently producing higher shear forces than the other locations. This outcome creates a concern as an increase in shear forces also produces an increase in rotational acceleration and risk of brain injury (King et al., 2003). It is important to highlight, however, that the interaction effect observed in the current study indicate that the system composed of neckform, helmet and headform managed the distribution of shear forces differently across helmet impact locations when the angle of impact was increased. Some of these differences across helmet impact locations in managing shear forces may be attributed not only to neck stiffness and angle of impact but also to the geometry of the helmet outer shell and liner (Graham, Rivara, Ford, & Spicer 2014). The results of this study provide an avenue to address the effect of neck torque on shear forces and this outcome can have implications in the development of helmet testing protocols and helmet designs. Finally, this study adds to the literature as neck stiffness, impact angle and impact locations have been examined independently in previous research (Haldin & Kleiven, 2013; Rousseau & Hoshizaki, 2009; Walsh, Rousseau, & Hoshizaki, 2011), but not extensively on their interaction with one another on measures of shear forces.

CONCLUSION: The outcome of the data highlights the need to further explore and develop testing protocols to better understand the ability of hockey helmets to manage shear impact forces to minimize possible diffuse axonal injuries in the brain that can lead to a concussion (King et al., 2003). Future research will explore the interaction effect of angle of impact, neck stiffness, and helmet location on energy dissipation as a possible avenue to better understand helmet ability to protect the head against trauma.

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