Influence of VN foam liner density on impact attenuation of an ice hockey helmet

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Introduction

The current Canadian Standards Association ice hockey helmet testing methodology utilizes a monorail drop to simulate falls (CSA, 2015). Linear acceleration is used as a performance criterion, which has been associated with skull fracture and traumatic brain injury (Gurdjian, 1966). Even though rotational acceleration known to more predictive of concussive injury (Gennarelli, 1971), it is not accounted for in standards testing.

Variations in external geometry (Spyrou, et al., 2000) and liner material type, thickness, and density (Newman, 1993; Post et al., 2011; Rousseau et al., 2009) can influence the protective capacity of a helmet. It would be beneficial to understand how liner material properties influence the helmet's ability to manage the linear and rotational acceleration forces of an impact.

The purpose of this study was to examine the influence of VN foam liner density on the impact attenuation of an ice hockey helmet.

Materials and Methods

Helmets: Three different densities of 0.5" vinyl nitrile (VN) foam liner (VN600, VN740, and VN1000) were cut to fit the inside of an ice hockey helmet (Figure 1). The outer shell from one model of a VN-lined helmet (CCM Vector 08) was used for all test impacts. The original Vector 08 liner (V08) was also tested.

Headform: A 50th percentile Hybrid III headform and unbiased neckform was equipped with nine single-axis accelerometers arranged in a 3-2-2-2 array (Padgaonkar et al., 1975). Accelerometer data was sampled at 20 kHz and filtered with a 1650 Hz low-pass Butterworth filter.

Monorail Drop Rig: Each VN liner type was impacted in the front, side, and rear at two impact velocities (4.5m/s and 6.5m/s). To align with standards testing, a Shore A MEP anvil was used (Figure 2).

Figure 1. Vector 08 (left) and VN 600 (right) helmet liners.

Figure 2. Monorail drop rig set-up depicting a rear impact.

Results

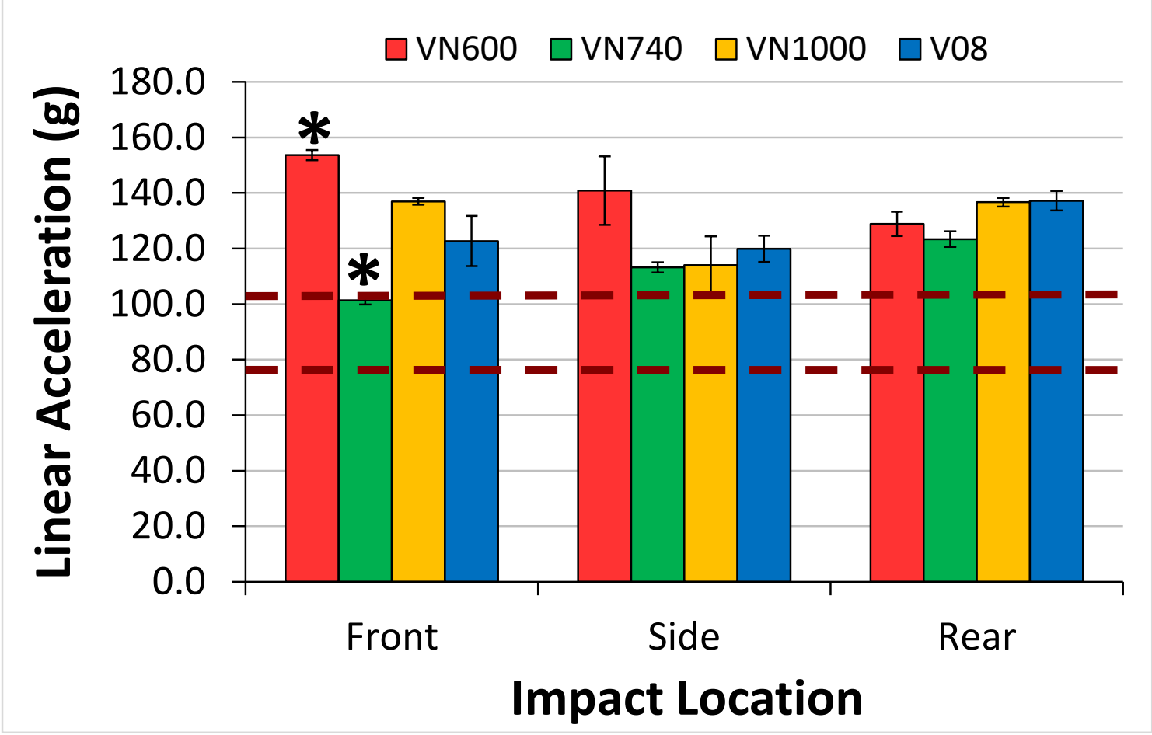

Figure 3. Mean linear acceleration, impacted at 4.5m/s. Area between dotted lines reflects the range of 50% likelihood of concussion (Fréchède & McIntosh, 2009; Newman et al., 2000).

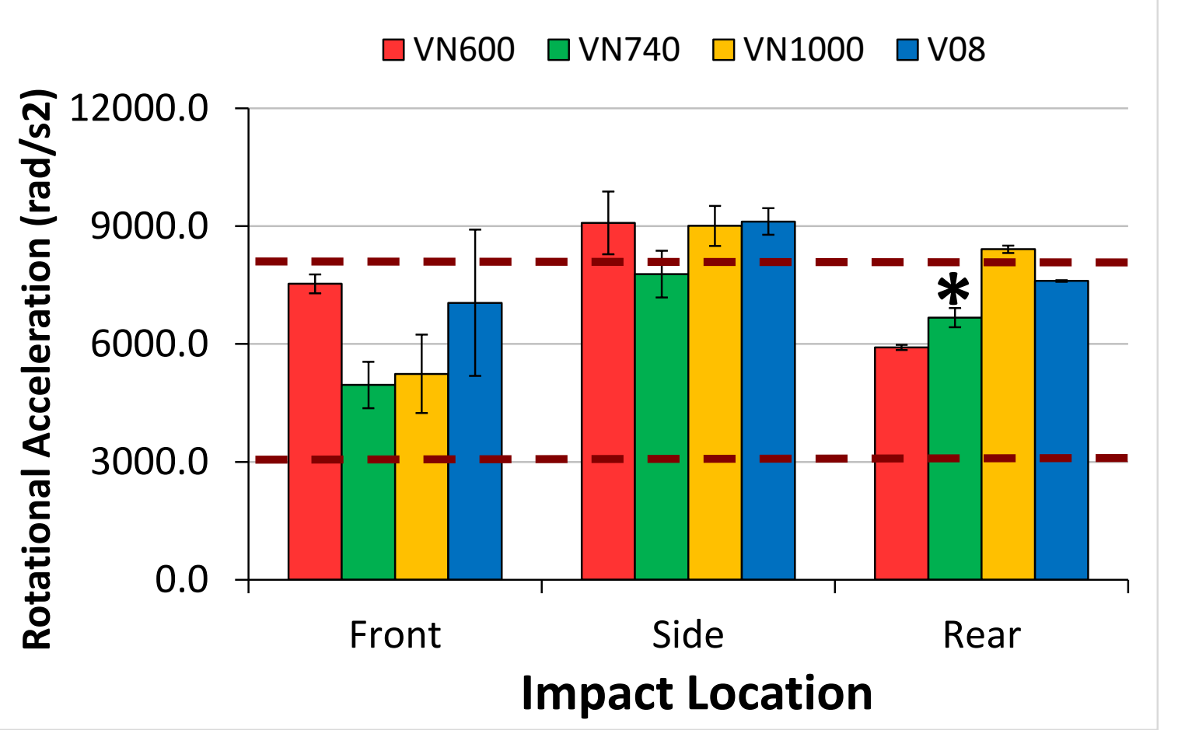

Figure 4. Mean rotational acceleration, impacted at 4.5m/s. Area between dotted lines reflects the range of 50% likelihood of concussion (Fréchède & McIntosh, 2009; Willinger and Baumgartner, 2003).

When impacted at 4.5m/s, all VN liners transmitted linear acceleration forces above a 50% threshold for concussion (Fig 3). The helmets yielded varying rotational acceleration values within the range of concussion (Fig 4). VN740 yielded the lowest linear acceleration at all impact sites and the lowest rotational acceleration in the front and side.

When impacted at 6.5m/s, all VN liners transmitted linear and rotational acceleration forces in excess of a 50% threshold for concussion (Fig 5 and 6). VN1000 and V08 most effectively managed linear acceleration, while VN740 most effectively managed rotational acceleration.

One-way ANOVAs were conducted to identify performance differences between liner types at each impact site. When significant differences were discovered, a post-hoc Tukey HSD Test was used to discriminate differences between individual liner types. Helmet liners that performed significantly different than the other three liner types ($p<0.05$) are denoted with an asterisk (*) in the figures.

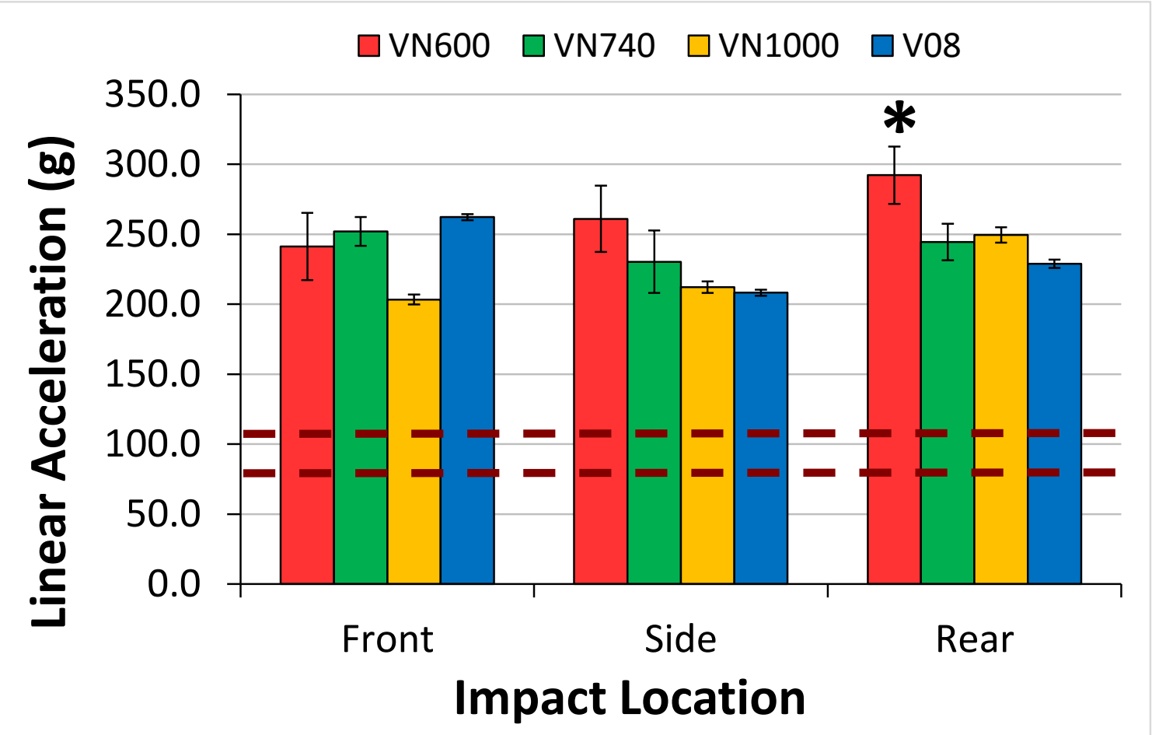

Figure 5. Mean linear acceleration, impacted at 6.5m/s. Area between dotted lines reflects the range of 50% likelihood of concussion (Fréchède & McIntosh, 2009; Newman et al., 2000).

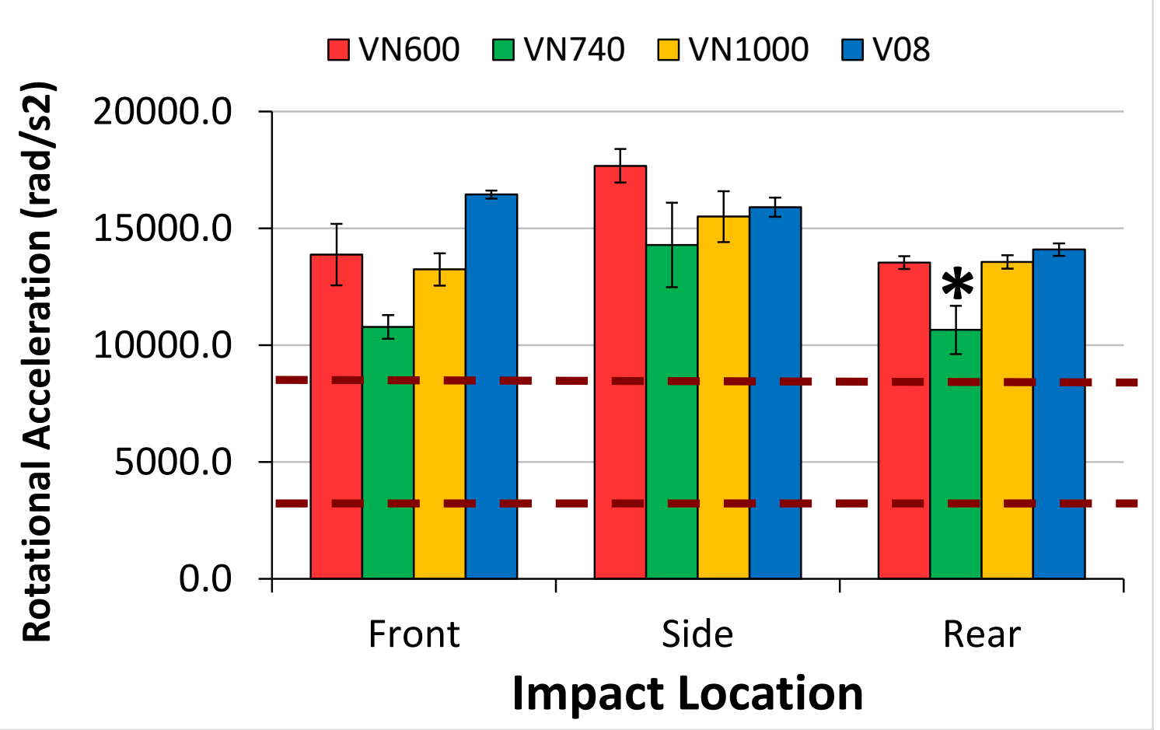

Figure 6. Mean rotational acceleration, impacted at 6.5m/s. Area between dotted lines reflects the range of 50% likelihood of concussion (Fréchède & McIntosh, 2009; Willinger and Baumgartner, 2003).

Discussion

Analysis of Material Performance: Each density of foam is expected to possess a unique functional range in which it can optimally attenuate the energy of an impact. When VN foam is compressed, it experiences a defined deformation pathway (Figure 7). A higher density increases the Young's modulus, raises the level of plateau stress, and lowers the point of densification (Gibson and Ashby, 2001).

The poor performance of the VN600 liner at 4.5m/s can be attributed to its low density. This resulted in the material compressing too quickly, reaching densification (premature material failure), and failing to dissipate the inbound energy. Conversely, the VN1000 liner was too dense for this energy range, failing to completely compress before transmitting energy to the headform (Avalle et al., 2001). The medium-density VN740 liner demonstrated the best energy attenuation; thus, it is an optimal material to dissipate the inbound energy at 4.5m/s.

Upon increasing the velocity to 6.5m/s, the VN1000 liner was most effective at mitigating linear acceleration forces. This higher energy level required a denser material to attenuate the energy. Interestingly, VN740 optimally managed rotational acceleration at 6.5m/s.

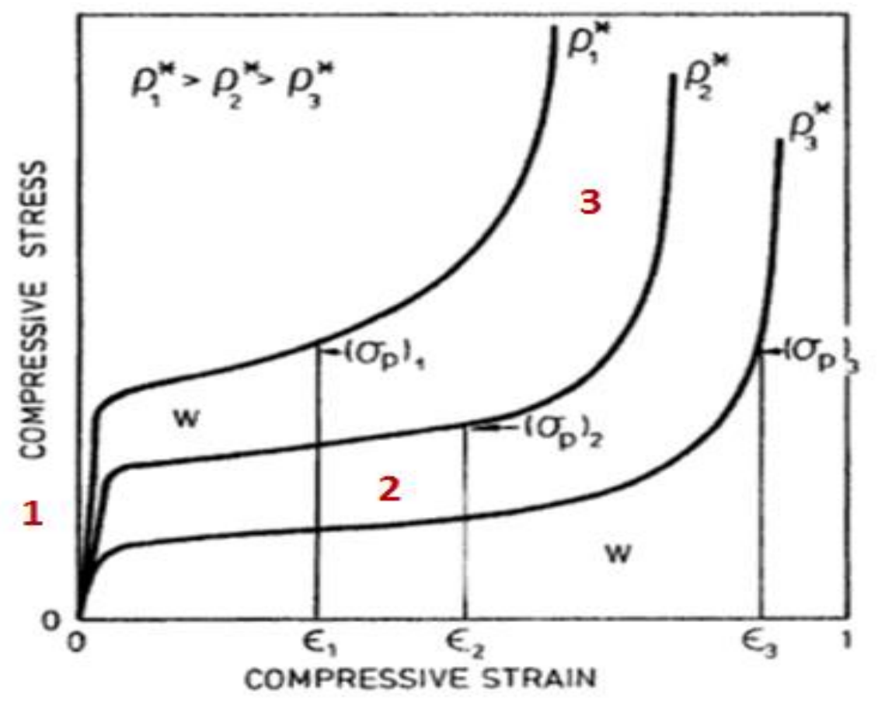

Figure 7. Compressive stress-strain response for three foams of increasing density. Foam experiences (1) linear elasticity, (2) plateau, and (3) densification (Gibson and Ashby, 2001).

Discussion (cont.)

Application to Brain Injury and Standards Testing: It is important to assess helmet materials based on their ability to reduce the risk of shear stress and concussive injury due to rotational acceleration (Gennarelli, 1971). At both impact velocities, the VN740 liner optimally compressed to reduce the rotation of the headform. However, impacts at 6.5m/s yielded dynamic response values greatly exceeding concussion thresholds. These impacts would result in certain injury, independent of liner type. Therefore, standards testing should be performed in the lower energy range. At 4.5m/s, there are more performance differences observed, thus providing a better method to evaluate the protective capacity of helmets.

Conclusion

This study demonstrated the influence of VN foam liner density on impact attenuation in an ice hockey helmet. The medium-density VN740 liner effectively managed rotational acceleration forces, thus reducing the risk of concussive injury. Additionally, standards organizations should perform test impacts at 4.5m/s to identify differences in protective capacity among helmets. In the future, it would be beneficial to examine the capability of this helmet testing methodology to identify differences associated with both the density thickness of VN foam liners. Furthermore, it would be beneficial to examine the performance of varying helmet material properties during collision impact events.

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