

A comparison of three rotational ice hockey helmet test protocols

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Abstract

Current ice hockey helmets have successfully decreased the incidence of traumatic brain injuries (TBI) in the sport; however, concussions are still a major issue (Goodman, D., Gaetz, M., and Meichenbaum, D., 2001). This may be due to helmets not being tested using rotational impacts and rotational measures which can be reflective of concussive impacts (CSA Z262.1-15). Meehan (MSc Thesis, 2019) proposed rotation dominant impacts that reflect concussive events experienced in ice hockey as a potential helmet testing protocol to improve the protective capacity of ice hockey helmets for concussion. The researchers reported a high compliance pneumatic ram test was the test most representative of shoulder to head concussive impacts in professional ice hockey however, it was not as repeatable as the medium compliance pneumatic ram test. For head impacts from falling into the boards, the 45° Anvil Drop test was closest to the mean 44° angle of impact for head to board events in professional ice hockey. These tests haven't been observed using multiple helmet designs to investigate their ability to distinguish between helmet performance.

The objectives of this thesis were to 1) determine if the Medium and High Compliance Pneumatic Ram tests and the 45° Anvil Drop test produce different magnitudes of dynamic response and brain tissue strain and 2) determine if the tests have the ability to distinguish changes in helmet design. The Medium Compliance Pneumatic Ram test produced the highest magnitudes of dynamic head response and strain followed by the 45° Anvil Drop and then the High Compliance Pneumatic Ram test. When the helmet designs in each test were compared, the 45° Anvil Drop test reported the most conditions (21) where there were significant differences in the dependent variables between helmets. The Medium Compliance Pneumatic Ram test reported 10 conditions with significant differences detected and the High Compliance Pneumatic Ram test reported 8 conditions with significant differences between helmets.

The most sensitive test protocol was the 45° Anvil Drop followed by the Medium Compliance then High Compliance Pneumatic Ram tests. The results showed that all of the tests produced different levels of rotational acceleration and MPS, which supports separate test protocols in terms of helmet testing standards. Information from this thesis can be used by standards organizations to guide the development of ice hockey helmet testing standards.

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Chapter 1: Introduction

Wennberg and Tator (2014) investigated the incidence of concussion in professional ice hockey (NHL) over ten regular seasons (1997-2008) reporting an average of 1.45 concussions over 1000 athletic exposures. Current hockey helmets have reduced the incidence of traumatic brain injuries (TBI); however, concussions are still a major issue (Goodman, D., Gaetz, M., and Meichenbaum, D., 2001). Hockey helmet manufacturers continue to search for ways to mitigate the risk of concussive injuries. Current hockey helmet testing standards employ linear drop tests, which represent a single type of impact event (fall to the ice) while only 7% of concussive injuries in professional ice hockey are caused by a fall to the ice, 88% of concussions are the result of player-to-player collisions (Hutchinson et al., 2015).

Meehan (MSc Thesis, 2019) proposed rotation dominant impacts that reflect concussive events experienced in ice hockey as a potential helmet testing protocol to improve the protective capacity of ice hockey helmets against concussion. The High Compliance Pneumatic Ram test revealed a similar impact duration to real world shoulder-to-head concussive injuries in contrast to the Medium Compliance Pneumatic Ram test which did not overlap with the real-world impacts in dynamic head response. However, between these two compliances it is uncertain if they are capable of detecting differences between helmet designs and therefore would be successful at measuring helmet performance. For head-to-boards impacts, the 45° Anvil Drop test was representative of these impact events in professional ice hockey however the sensitivity of this test has not been established.

The purpose of this thesis was to 1) determine if the Medium and High Compliance Pneumatic Ram tests and the 45° Anvil Drop test produce different magnitudes of dynamic response and brain tissue strain and 2) determine if the tests are sensitive to changes in helmet design to be successful at measuring helmet performance.

Limitations

1. The male 50th-percentile Hybrid III headform is closely representative of an adult head in terms of geometry and mass, however, it is not fully biofidelic (Deng, 1989; Kendall et al., 2012). This is because the aluminum skull cap and rubber skin material that is the headform's composition do not represent the true compliant nature of human skin tissue (Hodgson et al., 1971; Deng, 1989; Kendall et al., 2012)
2. The hockey helmets in this study are limited to 3 types of helmet liner and 1 shell model. The results of this study cannot be generalized to other brands or shell geometry of helmets other than the ones used in this study.
3. The University College Dublin Brain Trauma Model (UCDBTM) was used to determine the brain tissue strain from the head impact. This model was validated against the responses of cadaver head impacts which may not accurately predict the response of real human brain tissue (Nahum et al., 1977; Hardy et al., 2001; Horgan and Gilchrist, 2003, 2004).

Chapter 2: Review of Literature

2.1 Concussion in Ice Hockey

Brain injury occurs when there is an abrupt impact to the head that creates acceleration, deceleration, or deformation of the skull and brain (Gurdjian et al., 1964). These brain injuries are classified into traumatic brain injuries or more commonly in sport, mild traumatic brain injuries (mTBI) such as concussion. Fortunately, traumatic brain injuries are now far less prevalent in sports such as ice hockey in part due to the protective abilities of helmets however concussions are still quite common (Hoshizaki and Brien, 2004). Concussions have been described as a rotationally induced injury (Ommaya

and Gennarelli, 1974) and current ice hockey helmets are not tested for this type of impact characteristic. Wennberg and Tator (2003) investigated the incidence of concussion in professional ice hockey (NHL) over ten regular seasons between the years of 1997 to 2008. The authors reported an average of 1.45 concussions sustained per 1000 athletic exposures (a player on the ice). This is an increase from earlier years in professional ice hockey where the incidence rates were 6.4 concussions per 1000 games between 1986 and 1996, and 24.7 concussions per 1000 games between 1997 and 2002. There is a clear increase in concussion rates in professional ice hockey which further promotes the need for helmets to be developed for concussion specific impact parameters (Wennberg and Tator, 2003).

2.2 Impact Events

Ice hockey is played in a unique environment where head impacts are representative of a number of events. Falls into the glass, boards, and ice surface; as well as collisions with other players and the puck can all result in head impacts (Post et al., 2019). The head impact events associated with the concussive injury in elite hockey were categorized by Hutchinson and colleagues (2015) who investigated medically diagnosed concussions from the 2006-2007 season to the first half of the 2009-2010 season by reviewing digital video records. The authors reported that of the 197 concussions in 4299 regular season games; 88% of the concussions resulted from contact with another player and of those, over 40% were a result from shoulder-to-head impacts. Additionally, 37% of all the concussive injuries resulted from a fall into the boards or glass due to a collision with an opponent. Post and colleagues (2019) reconstructed the biomechanics of concussive and non-concussive impact events in elite ice hockey for regular season games from 2007-2014. The impact events were categorized as head impacts with boards, elbows, glass, ice, pucks, and shoulders. Eighty concussive head impacts and 45 head impacts events that did not result in a concussion were re-constructed. Of the concussive events, roughly 53% were due to shoulder-to-head

impacts, 16 % from elbow-to-head, 11% from head-to-glass, 9% from head-to-boards, 6% from puck-to-head, and 5% from head-to-ice.

The test methods observed in this thesis were designed to be representative of shoulder-to-head concussive injuries and head-to-board concussive injuries. The impact events that were identified possessed a unique set of impact parameters including velocity, location, direction and compliance. Impact direction was not included in this thesis because it was not included in the impact parameters proposed by Meehan and colleagues (2019). The effect of these impact characteristics on dynamic response of the head and resulting brain strain will be measured.

2.3 Impact Velocity

The effect of velocity, mass, and compliance on the severity of a head impact has been investigated in early work by Gurdjian et al. (1964). The researchers conducted unhelmeted and helmeted impacts from drop tests on the forehead of cadavers and also impacted the side with a weighted hammer (1 kg). The data reported a positive relationship between impact velocity and linear acceleration of the head (Gurdjian et al., 1964). In a more recent study, Oeur (2018) investigated the influence of impacts parameters on subsequent dynamic response and brain strain of the head. The study reported that between compliance, impact velocity, and mass; impact velocity was most influential for finite element strain ($\beta = 0.70-0.86$) for all locations except the side where compliance had a higher beta coefficient.

A study conducted by Post and colleagues (2019) determined mean velocities of concussive and non-concussive head impacts in elite ice hockey using Kinovea video software. Shoulder to head impacts resulting in concussion had a mean velocity of 7.50 (1.5) m/s and a mean velocity of 6.13 (1.3) m/s for non-concussive impacts. For head to boards and head to glass impacts, concussive impacts had mean velocities of 4.45 (1.2) m/s and 4.38 (0.8) m/s respectively and for non-concussive impacts the researchers reported 3.73 (1.0) m/s and 3.98 (1.5) m/s respectively.

For this thesis, the mean velocity for the linear impactor (7.5) and the angled drop test (4.5) were chosen one standard deviation above (9 m/s and 6 m/s, respectively) and one below (6 m/s and 3 m/s, respectively) to represent a range of velocities that impacts could occur at.

2.4 Impact Locations

Impact location is an important variable when investigating brain injuries as it provides information on the resulting directional motion of the head due to an impact. Post and colleagues (2014) reconstructed 20 falls that resulted in TBI to determine the influence of direction on type of brain trauma. Impacts to the occipital and frontal regions of the brain show higher risk of subdural hematoma compared to lateral impacts. Impacts to the head in the sagittal direction result in a “high degree of relative brain/skull motion” which is not the case for impacts to the side of the head (Post et al, 2015). Lateral impacts on the other hand are more likely to cause mTBI even at lower magnitude events (Post et al, 2015; Kleiven, 2003).

Concussive shoulder-to-head impacts and head-to-board impacts from the professional ice hockey data set was analyzed to determine the most common locations for those impact events (Meehan, MSc Thesis, 2019; Post et al., 2019). For shoulder-to-head impacts, the three most frequent impact locations were the front boss positive azimuth (FBPA), side, and rear boss negative azimuth (RBNA) locations. These locations are consistent with the University of Ottawa Test Protocol 5 (UOTP5) non-centric and centric locations (Walsh et al., 2012). For the head-to-board impacts, the three most common impact locations were the side, rearboss (RB), and rear locations.

2.5 Compliance of Impacting Surface

In elite men's ice hockey, concussive injuries occur from many different impact sources which all have unique surface compliances (Post et al., 2019). Compliance has been reported to have effects on risk of brain injury through the duration of an impact (Gennarelli, 1983; Gurdjian, Roberts, Thomas, 1966). There has been a positive relationship between the duration of the acceleration acting on the head and the resulting brain strain, even at a lower magnitude of acceleration. In ice hockey, researchers compared low (5 ms), medium (15 ms), and high (25 ms) compliance striker caps to determine their effect on the protective capacity of the helmets. de Grau et al., (2020) reported that hockey helmets are effective at reducing dynamic response and MPS at short duration (lower compliance) impacts. When compliance is increased, the protective abilities of helmets decrease. The findings from this study support the importance for helmets to be tested using higher compliance conditions representative of player-to-player collisions to aid in designing helmets for protection from these impacts.

2.6 Helmet Type

Evaluation of helmet protection requires researchers and helmet manufacturers to determine the dynamic head response or brain deformation variables that best identify differences that may exist between helmet performance. Rousseau, Post, and Hoshizaki (2009) investigated how current hockey helmet liners (vinyl nitrile (VN), expanded polypropylene (EPP)) manage dynamic head response at 5, 7, and 9 m/s for front, deflected, and front boss locations. They reported that although the VN and EPP liners perform similarly for linear impacts, differences existed in the rotational responses. Similar results were reported by Walsh and colleagues (2011) using centric and non-centric impact locations at a velocity of 7.5 m/s to compare the safety performance of six certified ice hockey helmets.

This thesis consisted of the use of both VN and EPP liners to determine if the helmet test protocols were able to distinguish between performance of the foams. In addition, a prototype helmet which

contained decoupling technology was used to provide an alternate protection mechanism to further determine the sensitivities of the tests. The concept of decoupling results in a reduced friction between the head and the helmet. Ideally, this interaction transfers a portion of the normal force on the head into a tangential force which ultimately reduces the motion of the head and thus, the brain (Taylor et al., 2018).

2.7 Measuring Helmet Performance

2.7.1 Linear Acceleration

Linear acceleration is a common metric used to predict the risk for traumatic brain injuries including skull fracture. Gurdjian and colleagues (1966; 1968) studied intracranial pressure changes during impacts on animals in an attempt to correlate biomechanical variables with brain damage. They reported pressure changes as a potential mechanism of injury by creating shear stress on the brain. Deformation of the skull and its acceleration after an impact results in pressure changes, meaning, if the kinematics of an impact can be measured than the risk of injury could be better predicted (Gurdjian et al 1968; Post et al 2011). More recently, Nuscholtz et al (1987) performed head impacts on adult Macaque monkeys to investigate the correlation of linear acceleration and intracranial pressure. Their research also confirmed this relationship. The use of peak resultant linear acceleration as a performance measure in sport helmets has successfully reduced the prevalence of traumatic brain injuries (Hoshizaki and Brien, 2004).

2.7.2 Rotational Acceleration

Linear acceleration has been considered a metric leading to concussion while the biomechanics of concussion has suggested that this is likely not be the case (Bishop, 2009). Holburn and colleagues (1943) were the first to identify rotational acceleration to be associated with concussive injury. They reported the

high bulk modulus and low shear modulus of brain tissue make it more vulnerable to shear-strains than compression. This was demonstrated by impacting a gelatin model of the brain and reporting the model to be more sensitive to shear forces compared to compressive forces (Holburn et al 1943). This theory was investigated by Gennarelli et al (1972) by performing head impacts on monkeys. They found concussion to be a result of rotational acceleration more so than linear acceleration. Investigators found it difficult to induce concussions in the animals using solely linear acceleration. In 12 of 25 impacts using linear acceleration alone, the monkeys did not exhibit concussive injury (Gennarelli et al 1972).

Specifically in sport, concussions can result from long duration, low magnitude impacts resulting in rotational motion of the head and brain (Holburn et al. 1943, Gennarelli et al. 1972, Post et al. 2012). These impacts are more likely to happen in ice hockey as nearly all head impacts are eccentric (not through center of gravity), resulting in rotational head motion (Bishop, 2019). Finite element analysis of head impacts also reported rotational acceleration as more influential on brain tissue strain than linear acceleration (Zhang et al 2006). Post and colleagues (2011, 2012, 2013) analyzed the correlations between linear and rotational acceleration and MPS in ice hockey and football helmets. The studies reported peak rotational acceleration correlated with strains (MPS) in multiple brain tissues while linear acceleration did not report similar correlations.

2.7.3 Rotational Velocity

There has been a substantial amount of research involving the role of peak rotational acceleration and velocity in predicting brain injury. Rotational velocity has been used to differentiate between concussive and non-concussive impacts in sport (McIntosh et al, 2014) as well as correlate highly with MPS (Takhounts et al, 2013). Meehan (MSc Thesis, 2019) related three ice hockey helmet tests to reconstructions of concussive injuries in professional ice hockey. A stepwise regression analysis was performed to determine which variables were correlated with MPS for each test method (Flat drop, angled

anvil, pneumatic ram test). For the 45-degree anvil drop test, dominant rotational velocity was the variable with the strongest correlation to MPS ($R^2 = 0.977$, $p < 0.001$). This correlation demonstrates rotational velocity as being a useful performance measure for rotational helmet tests as well as correlating with risk of concussive injury.

2.8 Brain Tissue Deformation

2.8.2 Finite Element Modelling

Three-dimensional finite element (FE) modeling has become the most accurate method for evaluating brain tissue strain and assisting in predicting injury risk by modeling the human skull and brain anatomically (Horgan and Gilchrist, 2003; Kleiven, 2007; Willinger and Baumgartner, 2003; Zhang et al., 2001). FE models decompose the skull and brain into thousands of small elements which are assigned material properties to represent the tissue each element corresponds with. For this thesis, the dynamic response loading curves were input into the University College Brain Trauma Model (Horgan and Gilchrist, 2003) to output maximum principal strain values.

2.8.3 Maximum Principal Strain

Dynamic response time curves of head motion during impact in conjunction with finite element modeling is used to obtain strain values for brain tissue (Viano 2005, Zhang 2006, Casson 2010, Kleiven 2013, Patton 2015, Kleiven 2015). Maximal principal strain (MPS) is used to represent the stretch that occurs to brain tissue during a head impact and has been used to predict risk of concussive injury (Kleiven 2007, Zhang et al 2004, Post et al 2012, Hoshizaki et al 2014). Zhang (2004) reconstructed 24 helmet to helmet impacts in football using velocities and locations calculated from video analysis to evaluate risk

of mTBI using the Wayne State Brain Injury Model. From the reconstructions, strain thresholds were reported at 0.14, 0.19, and 0.24 for 25%, 50%, and 80% chance mTBI, respectively. Kelvin (2007) demonstrated that MPS had the ability to distinguish between concussion and non-injury impacts in American football in all regions of the brain with exemption of the brain stem.

2.9 Summary of Current Standards

Canadian Standards Association standard testing for ice hockey helmets use a monorail system guiding the acceleration of helmeted headform onto a flat modular elastomer programmer anvil (CSA Z262.1-15). A CEN EN 960 magnesium headform fitted with a uniaxial accelerometer is dropped onto a 25 mm 60 ± 5 Shore A MEP Pad Anvil at 4.5 m/s. The locations impacted include Crown, Front, Front Boss, Side, Rear Boss, Rear. The standard uses a pass/fail linear acceleration-based injury metric (275g) which results in helmets designed to prevent TBI. This type of standard has been successful at significantly decreasing the incidence of TBI, however, since concussions are primarily the result of rotational acceleration, it has done little to minimize the risk for concussive injuries (Hoshizaki and Brien, 2004). Standards tests also use a headform that is rigidly attached to the drop system, which predominantly allows linear acceleration to occur. The current standard is representative of an individual falling onto ice, which is not as common in elite ice hockey compared to head-to-shoulder/elbow impacts or head-to-boards/glass impacts (Hutchinson et al., 2015; Post et al., 2019). While it is still important to represent falls to the ice because of a higher risk of TBI; to establish whether ice hockey helmets are effective in managing the risk of concussion, standards testing protocols should include tests that create rotational impact tests to mimic conditions known to produce concussive injury.

2.9.1 Rotational Test Methods

The current standard testing for ice hockey captures one head impact event type (head-to-ice). As a result, helmets are not designed to protect against concussion, a rotationally induced injury. However, some rotational tests have been standardized for other sports. The European Committee for Standardization (CEN) proposed a standard test for cycling and equestrian helmets using a 45° Anvil Drop test to represent a head impact inducing rotation. The NOCSAE pneumatic ram test is a rotational standard test for American football helmets that includes centric and non-centric impacts using a linear impactor (NOCSAE DOC 002-17m17a). Although there are currently no standards tests measuring rotational motion for ice hockey, researchers have proposed test methods which induce rotation and reflect how concussions occur in ice hockey. Meehan and colleagues (2019) modified the parameters of the angled drop test and linear impactor to represent concussive injuries in professional ice hockey. They set the velocities and locations as discussed earlier in the literature review for each of the tests to determine how strongly they correlate with real world concussions resulting from head-to-boards and shoulder-to-head impacts (Post et al, 2019). For the linear impactor (Pneumatic Ram Test), two levels of compliance were used; medium and high, and for the angled drop test two angled anvils were used; 30° and 45°. The 30° and 45° Anvil Drop tests captured similar levels of strain (MPS), however, the 45° anvil drop test was more similar in angle to what was measured in video analysis of real-world head-to-board impacts (mean = 44°) (Meehan, MSc Thesis 2019). Therefore, for this thesis the 45° Anvil drop test was used to capture head-to-boards impacts in a helmet test protocol. For the pneumatic ram test, both of the compliance levels demonstrated rotational acceleration to have the strongest correlation with MPS. The high compliance impactor, however, was more similar to the shoulder-to-head reconstructions in terms of rotational acceleration and the impact duration (25 ms). On the contrary, the medium compliance impactor reported more consistent acceleration loading curves than the high compliance, which was due to material of the

striker cap deforming upon impact in the high compliance condition. The researcher's concluded that the medium compliance impactor is a more repeatable helmet test but is not as representative of shoulder-to-head concussive impacts as the high compliance impactor. Although the researcher has demonstrated correlations between the 45° anvil drop and the high and medium compliance pneumatic ram tests and real-world concussive injuries in professional ice hockey; it is still unknown if statistically the three tests produce different levels of response and brain strain. It is also unknown if the tests are capable of distinguishing between different helmet technologies.

Summary

Ice hockey is a sport with a reported high incidence of concussions resulting from many different events including collisions between players (shoulder-to-head) and falls into the boards (head-to-boards) which induce rotation of the head. While concussions are associated with rotational kinematics of the head, current helmet standards testing for ice hockey do not include rotational methods for evaluating the helmets. Although the High and Medium Compliance Pneumatic Ram tests and the 45° Anvil Drop test have been reported to be representative concussive impacts in professional ice hockey, they have not been tested with more than one model of hockey helmet to investigate their abilities to distinguish between helmet design. In terms of providing information for standards testing, it is also unknown if the three tests produce statistically different levels of dynamic head response and MPS from one another. This thesis will compare the rotational helmet tests to determine if they are statistically different from one another for dynamic response and MPS. This research will also compare the ability of the test methods to identify performance differences between hockey helmet designs. The information from this thesis will inform the development of ice hockey helmet standards as well as helmet designers.

Chapter 3: Research Design

3.1 Research Questions

- 1) Is there a significant difference in dynamic response and brain tissue deformation between the 45° drop test, the medium compliance pneumatic ram test, and the high compliance pneumatic ram test?
- 2) Is there a significant difference in dynamic response and brain tissue deformation between the bare-headform, the VN helmet, the EPP helmet, and the fluid helmet, on dynamic head response and brain tissue deformation for each of the test protocols?

3.2 Objective

- 1) To compare the dynamic head response and brain tissue deformation for three test protocols (45° Drop Test, Medium Compliance Pneumatic Ram Test, High Compliance Pneumatic Ram Test).
- 2) To compare the dynamic head response and brain tissue deformation for each helmet condition (Bare-headform, VN, EPP, Fluid) on each test protocol.

3.3 Independent Variables

- Three impact test protocols
 - 45° drop test
 - Pneumatic ram test high compliance
 - Pneumatic ram test medium compliance

- Four impact conditions
 - Bare headform
 - Vinyl nitrile helmet (VN)
 - Expanded polypropylene helmet (EPP)
 - Fluid prototype helmet (FLUID)

3.3 Dependent Variables

- Dynamic response (peak resultant)
 - Linear acceleration (g)
 - Rotational acceleration (rad/s²)
 - Rotational velocity (rad/s)

- Brain tissue deformation
 - Maximum principal strain (%)

3.4 Null Hypothesis

1) There will be no significant difference in peak resultant linear acceleration between the 45 drop test, the medium compliance pneumatic ram test, and the high compliance pneumatic ram test for each helmet condition.

2) There will be no significant difference in peak resultant rotational acceleration between the 45 drop test, the medium compliance pneumatic ram test, and the high compliance pneumatic ram test for each helmet condition.

3) There will be no significant difference in peak resultant rotational velocity between the 45 drop test, the medium compliance pneumatic ram test, and the high compliance pneumatic ram test for each helmet condition.

4) There will be no significant difference in MPS between the 45 drop test, the medium compliance pneumatic ram test, and the high compliance pneumatic ram test for each helmet condition.

5) There will be no significant difference in peak resultant linear acceleration between the VN helmet, the EPP helmet, and the fluid helmet using each test protocol.

6) There will be no significant difference in peak resultant rotational acceleration between the VN helmet, the EPP helmet, and the Fluid helmet using each test protocol.

7) There will be no significant difference in peak resultant rotational velocity between the VN helmet, the EPP helmet, and the Fluid helmet using each test protocol.

8) There will be no significant difference in MPS between the VN helmet, the EPP helmet, and the Fluid helmet using each test protocol.

3.5 Research Design

The test design consisted of three trials at three velocities and three locations for each of the four helmet conditions (3x3x3x4) for a total of 108 impacts for each test protocol. Below is the fully crossed research design of the impacts for the test protocols.

		A1	A2	A3
	B1	A1B1C1	A2B1C1	A3B1C1
C1	B2	A1B2C1	A2B2C1	A3B2C1
	B3	A1B3C1	A2B3C1	A3B3C1
	B1	A1B1C2	A2B1C2	A3B1C2
C2	B2	A1B2C2	A2B2C2	A3B2C2
	B3	A1B3C2	A2B3C2	A3B3C2
	B1	A1B1C3	A2B1C3	A3B1C3
C3	B2	A1B2C3	A2B2C3	A3B2C3
	B3	A1B3C3	A2B3C3	A3B3C3
	B1	A1B1C4	A2B1C4	A3B1C4
C4	B2	A1B2C4	A2B2C4	A3B2C4
	B3	A1B3C4	A2B3C4	A3B3C4

A= Impact Location
B= Impact Velocity
C= Helmet Test Condition

3.6 Statistical Analysis

Two-Way ANOVA Test

Mean resultant linear acceleration, rotational acceleration, rotational velocity, and MPS were compared between each of the three test methods (averaged across all velocities and locations) using a Two-Way ANOVA test. This test was used to determine if there were any significant interactions between the independent variables. This will also determine if there was a main effect of the independent variables on the dependent variables. Tukey post hoc tests were also performed to determine which comparisons

resulted in significant differences. An alpha level of 0.05 was used to determine significance. All of the data was analyzed using IBM SPSS for Mac (IBM Inc, Armonk, NY, USA).

One-Way ANOVA Test

One-Way ANOVAs were conducted to make comparisons between the four different helmet conditions within each of the test methods comparing each of the four dependent variables listed above. An alpha level of 0.05 was used to determine significance. All of the data was analyzed using IBM SPSS for Mac (IBM Inc, Armonk, NY, USA).

Pearson Correlations

Each dynamic response variable was plotted against MPS and the Pearson correlations (r) were calculated. MPS is the ‘gold standard’ for measuring brain trauma in sport and therefore determining which dynamic response variable demonstrated the strongest relationship with MPS would provide information for using a performance metric for each of the test protocols. Alpha was set at 0.05 to determine significance.

Chapter 4: Methods

4.1 Test Procedure

Each helmet was impacted three times at each location for a total of 9 impacts per helmet (3x3) for each test protocol. When the velocity was changed, a new helmet was used. Therefore, there were three helmets used for each of the test protocols. Three trials/impacts were collected per location (3), per velocity (3), per helmet condition (4) and per protocol (3) resulting in a total of 324 impacts.

4.2 Helmet Test Protocols

4.2.1 45° Drop Test

The 45° Drop Test was used to represent head-to-boards impacts and is similar to the mean angle of impact (44°) analyzed in videos of head-to-board impacts in professional ice hockey (Meehan MSc Thesis, 2019). The monorail drop rig was used for this test which was derived from the proposed CEN test method (Halldin, 2015). The CEN test uses a 45° steel anvil covered with sandpaper; however, for this thesis the bare steel anvil was used to represent the low friction surface of hockey boards.

The helmeted and bare headform was impacted at three locations: side, rearboss (RB), and rear (Figure 1.). These locations were chosen as the most common locations for concussive head-to-boards impacts in professional ice hockey (Post et al, 2019; Meehan MSc Thesis, 2019). The mean velocity from that data set was 4.5 m/s with an SD of 1.5 and therefore, the velocities chosen for this thesis were 3.0, 4.5 and 6.0 m/s to capture the range of velocities that concussive head-to-boards impacts could occur.

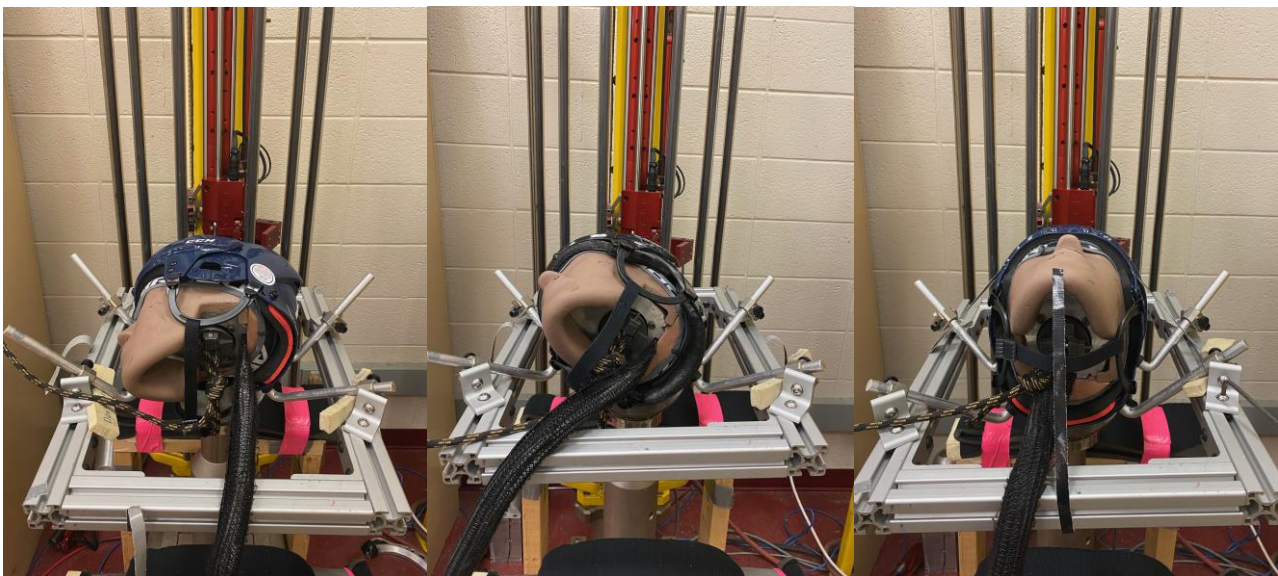


Figure 1. Locations for the 45° Drop Test: side (left), rearboss (middle), and rear (right)

4.2.2 Pneumatic Ram Tests

The pneumatic ram tests in this thesis were representative of shoulder-to-head impacts using two different levels of compliance and used a pneumatic linear impactor. Currently, ice hockey helmets standards tests do not assess the performance abilities of the helmets using compliant impact conditions. However, in professional ice hockey, concussive shoulder-to-head impacts have a reported mean impact duration of 25 milliseconds (ms) with durations ranging from 18 to 32 ms (Rousseau, 2014). Thus, this thesis consisted of both a high compliance and medium compliance impacting cap to capture the range of reported durations (de Grau et al, 2020).

The high compliance impacting cap (mass = 0.463 ± 0.001 kg) consisted of a 0.111 ± 0.001 m thick layer of 405S DER-TEX foam (DER-TEX Corp., Saco, ME, USA) covered with a 0.037 ± 0.001 m thick VN cap. This impacting cap produced an average impact duration of 25 ms (de Grau et al, 2020). The medium compliance impacting cap (mass = 0.368 ± 0.001 kg) consisted of a 0.041 ± 0.001 m thick layer of VN foam covered with a 0.037 ± 0.001 thick rounded VN cap. This impacting cap produced an average impact duration of 15 ms (de Grau et al, 2020).



Figure 2. The high (left) and medium (right) compliance impactor caps with 25 and 15 ms durations, respectively.

The helmeted and bare headform was impacted at three locations: front boss positive azimuth (FBPA), side, and rear boss negative azimuth (RBNA) (Figure 3.). The impact locations are consistent with the University of Ottawa Testing Protocol (Walsh et al., 2012) and produce non-centric impacts in the front and rear boss locations. These locations were chosen as the most common locations for concussive shoulder-to-head impacts in professional ice hockey (Post et al, 2019; Meehan MSc Thesis, 2019). The mean velocity from that data set was 7.5 m/s with an SD of 1.5 and therefore, the velocities chosen for this thesis were 6.0, 7.5 and 9.0 m/s to capture the range of velocities that concussive head-to-boards impacts could occur.



Figure 3. Impact locations for the pneumatic ram tests viewed in the sagittal, frontal, and transverse planes with the impact vectors indicated by the arrows.

4.3 Helmets

The helmets used for the tests in this thesis were medium sized CCM 50 (VN) and XT99 (EPP) hockey helmets which are both CSA-certified. The liner for the 50 was VN foam with a width of 0.0165m at the front, 0.0095m at the side, and 0.0160m at the rear of the helmet (Figure 4.). The XT99 helmet contained EPP foam and a comfort foam layer with a width of 0.0100m at the front, 0.0160m at the frontboss and side, and 0.0200m at the rear (Figure 4.). The prototype helmet was constructed using the XT99 helmets with oil filled pods arranged to align with the impact locations of the tests. The comfort foam was removed to keep the offset of the helmet consistent. The helmets were all equipped with the same shell geometry to isolate differences solely to the liner material (Figure 5.). A Bare headform condition was also used in this thesis as a baseline for the higher compliance impacts (Pneumatic Ram tests).



Figure 4. CCM 50 helmet with VN foam (left, CCM XT99 helmet with EPP liner with comfort foam (middle), prototype helmet using the XT99 helmet with oil filled pods (right).



Figure 5. Front and side view of the helmet shells for the 50 (left), XT99 (middle), and Prototype (right) helmets

4.3 Test Equipment

4.3.1 Pneumatic Linear Impactor

The pneumatic linear impactor was used to simulate player-to-player collisions resulting in shoulder to head impacts (Post et al., 2011; Walsh et al., 2011). The impactor consists of a frame, impacting arm, and a table in which the Hybrid III head-form was supported by an unbiased neckform (Walsh et al., 2018). The table where the headform is set up allows the dummy to slide backwards for a realistic response from the impact. The table is also motorized to allow for the headform to be raised or lowered to the desired

position for impact. There is a compressed air canister and piston, which is supported by the frame that will accelerate the impacting arm horizontally into the helmeted head-form. To represent shoulder impacts between an opposing player and the head, the mass of the impacting arm was 13.1 kg, which is similar to the mass of a shoulder in this type of impact in ice hockey (Rousseau et al., 2014). The velocity of impact will be measured by a photoelectric time gate, which is placed just prior to the impact (0.02 m) (Figure 6.).

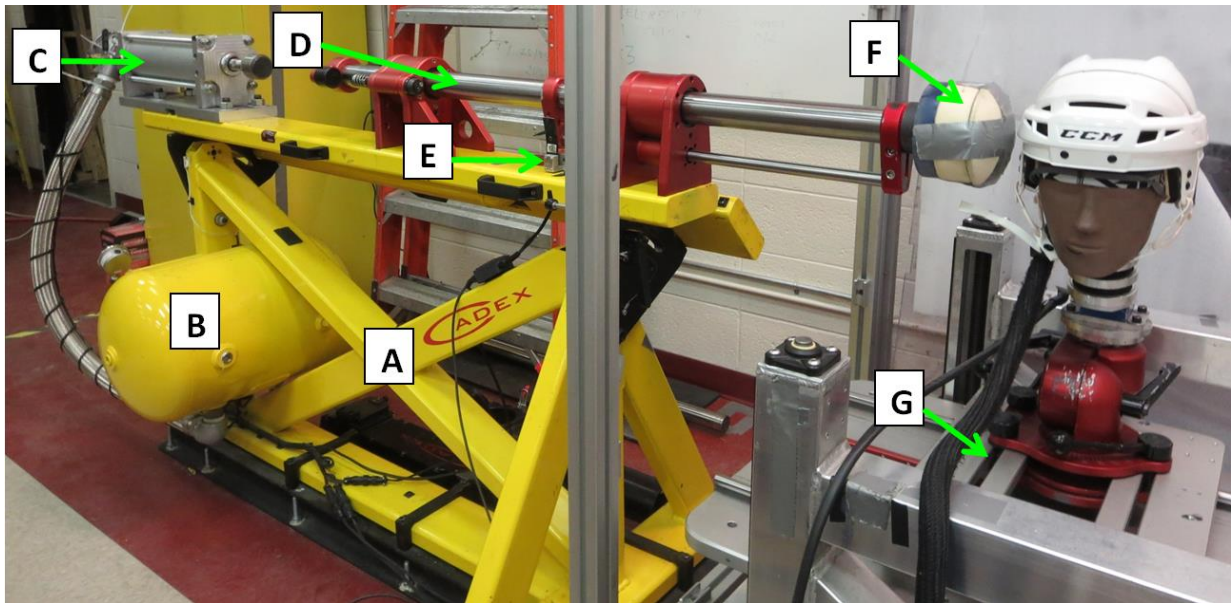


Figure 6. Pneumatic linear impactor consisting of a steel frame (A), compressed air tank (B), piston chamber (C), impacting arm (D), time gate (E), impacting cap (F), sliding table (G). (Meehan MSc Thesis, 2019)

4.3.2 Monorail Drop Rig

The monorail was used to simulate helmeted head impacts with the boards (Post et al., 2017; Meehan MSc Thesis, 2019). The monorail consists of a 4.7 m long rail where the drop carriage is attached. The drop carriage runs along the rails on ball bearings to reduce the effects of friction on velocity. A 50th-percentile Hybrid III head-form was placed on a supporting plate, which was attached to the drop carriage

to collect the dynamic head response at impact. The head form was not attached to a guided neckform to allow for unbiased movements in all axes (X, Y, Z). To measure velocity at impact, the monorail is suited with a photoelectric time gate which is placed within 0.02 m of the impact.

A 45-degree steel anvil, which the headform made contact with, is at an angle and compliance to replicate head impacts from falling into the boards (Meehan Thesis, 2019). The base of the monorail is 0.67 m high, 0.30 m wide, and 0.38 m deep and is fixed to the floor with 6 concrete bolts. The vertical track is bolted to the wall and the ceiling, which minimizes movement of the system and reduces the amount of background noise (Figure 7.).

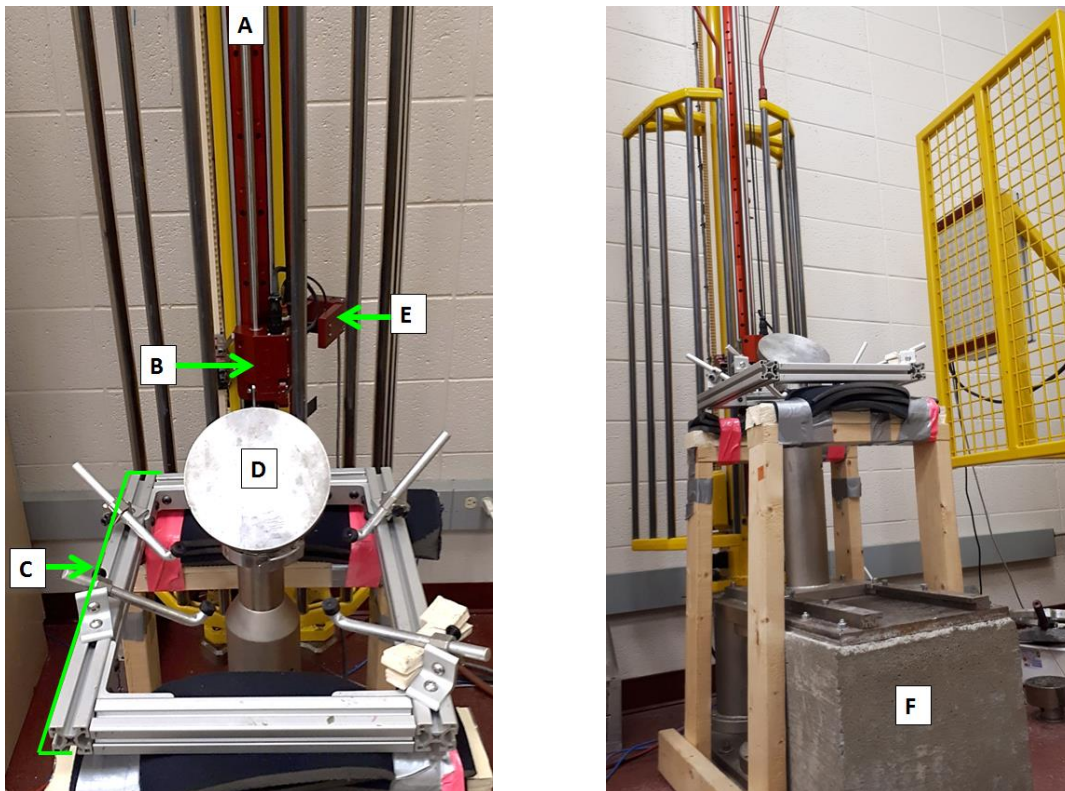


Figure 7. Monorail drop rig shown with vertical rail (A), motorized released system (B), drop carriage (C), 45° steel anvil (D), time gate (E), concrete base (F). (Meehan MSc Thesis, 2019)

4.3.3 Hybrid III Headform

A 50th percentile Hybrid III headform (m=4.54 kg) was used for this study with the addition of an unbiased neckform for the linear impactor trials. The headform was originally designed as part of General Motors testing as a human surrogate for automotive crashes (Hubbard and Mcleod, 1974). The headform has been shown to report acceleration data within ranges observed in drop tests with cadavers (Figure 8.) The Hybrid III headform is fitted with nine single axis Endevco 7264C-2KTZ-2-300 accelerometers which are positioned in a 3-2-2 array allowing for determination of the three-dimensional motion of the head. Three accelerometers were placed at the headform's center of gravity and two accelerometers were mounted at the top, front, and side of the headform (Figure 9.).

The accelerometer data was sampled at 20 kHz and collected using the TDAS Pro Lab system and (DTS, Seal Beach, California, USA). The direction of the head will be measured by observing accelerations in x (frontal), y (lateral), and z (vertical) axes during an impact.



Figure 8. The Hybrid III headform demonstrating the interior steel shell (left) and the external vinyl skin (right) (Meehan MSc Thesis, 2019).

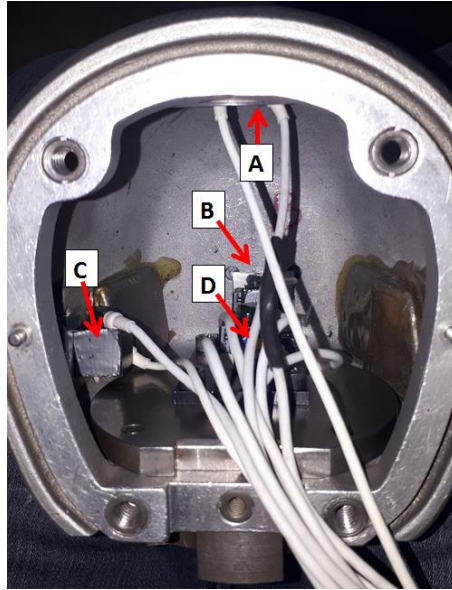


Figure 9. Posterior view of accelerometers inside the Hybrid III headform. Two accelerometers at the top (A), the front (B), and the side (C). Three accelerometers are also mounted at the center of gravity (D).

To calculate rotational accelerations in the x, y, and z axes; the following equation was used:

$$\vec{\alpha}_x = \frac{\vec{a}_{zS} - \vec{a}_{zC}}{2S} - \frac{\vec{a}_{yT} - \vec{a}_{yC}}{2T}$$

$$\vec{\alpha}_y = \frac{\vec{a}_{xT} - \vec{a}_{xC}}{2T} - \frac{\vec{a}_{zF} - \vec{a}_{zC}}{2F}$$

$$\vec{\alpha}_z = \frac{\vec{a}_{yF} - \vec{a}_{yC}}{2F} - \frac{\vec{\alpha}_{xS} - \vec{a}_{xC}}{2S}$$

The variable α_i represents rotational acceleration for i (x, y, z) components and the variable a_{ij} represents linear acceleration component i along the orthogonal arm j (F, S, T) (Padgaonkar et al., 1975). The coordinate system for $x, y,$ and z was defined by the right-hand rule seen in Figure 5.

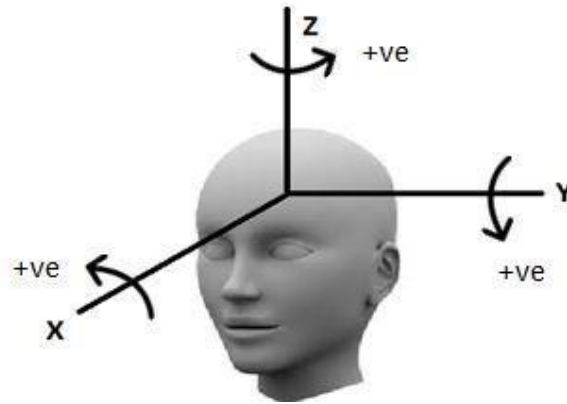


Figure 10. Coordinate system defined by the right-hand rule.

4.3.4 Unbiased Neckform

The unbiased neckform was used in this thesis to account for the mechanical biased that results from the Hybrid III neckform. The Hybrid III neckform was designed along with the Hybrid III headform at the General Motors Research Laboratory to maintain characteristics based on biomechanical data (Foster, Kortge, and Wolanin, 1977). Specifically, anteroposterior movement was a focus of this design resulting in a bias in this plane of motion (Foreman and Hoshizaki, 2011). Therefore, the unbiased neckform was developed at the University of Ottawa by researchers to promote unbiased motion in all directions and matched with the mass and dimensions of the Hybrid III neckform (Walsh et al, 2018).

4.4 University College Dublin Brain Trauma Model

There were 311 acceleration time curves from this thesis that were input into the University College Dublin Brain Trauma Model (UCDBTM) at the centre of gravity (Horgan and Gilchrist, 2003) to obtain MPS values. The simulations were run using Abaqus software (Dassault Systèmes, Waltham, MA, USA).

The finite element model defines shear behaviour of the brain tissue as viscoelastic and the compressive behavior as elastic (Horgan and Gilchrist, 2003). The researchers developed the geometry of the model using MRI and CT scans of male human cadavers' heads which include 26,000 hexahedral elements. The UCDBTM consists of 10 components (the scalp, skull, pia, falx, tentorium, cerebrospinal fluid (CSF), grey and white matter, cerebellum and brainstem) and Table 1. and Table 2. describe its material properties.

Table 1. Material properties of the UCDBTM

Material	Young's modulus (Mpa)	Poisson's ratio	Density (kg/m³)
Scalp	16.7	0.42	1000
Cortical Bone	15000	0.22	2000
Trabecular Bone	1000	0.24	1300
Dura	31.5	0.45	1130
Pia	11.5	0.45	1130
Falx	31.5	0.45	1140
Tentorium	31.5	0.45	1140

CSF	-	0.50	1000
Grey Matter	Hyperelastic	0.49	1060
White Matter	Hyperelastic	0.49	1060

Table 2. Material characteristics of brain tissue in the UCDBTM

Material	G_0	G_∞	Decay constant	Bulk modulus (s^{-1})
Cerebellum	10	2	80	2.19
Brain Stem	22.5	4.5	80	2.19
White Matter	12.5	2.5	80	2.19
Grey Matter	10	2	80	2.19

Equation 3. describes the shear characteristics and viscoelastic nature of the brain tissue:

$$G(t) = G_\infty + (G_0 - G_\infty) e^{-\beta t}$$

where G_∞ , is defined as the long-term shear modulus, G_0 , is the short-term shear modulus, and β is the decay factor (Horgan & Gilchrist, 2003).

Chapter 5: Results

5.1 Comparisons between test methods

A Two-Way ANOVA was performed to determine the effect of test protocols on peak resultant linear acceleration, rotational acceleration, rotational velocity, and MPS. This test was also used to determine if there was a significant interaction between the test protocols and the helmet conditions. The data for the three velocities and three locations for each test were combined for this portion of the analysis.

Table 3. Comparison of overall means (standard deviations) of dynamic response and brain tissue deformation between the High/Medium Compliance Pneumatic Ram (PR) and 45° Anvil Drop Tests.

Test Protocol	Resultant			MPS
	Linear acceleration (g)	Rotational acceleration (rad/s ²)	Rotational velocity (rad/s)	
High Compliance PR	20.8** (4.3)	2290** (619)	23* (4.8)	0.225** (0.036)
45° Anvil Drop	56.5* (26.2)	4269** (2542)	25.5* (13.2)	0.331** (0.183)
Medium Compliance PR	50.7* (11.8)	4969** (1445)	35.5** (7.9)	0.438** (0.094)

* = significant difference ($p < 0.05$) from one test; ** = significant difference from both other tests

There was no significant interaction between the test protocols and the helmet conditions ($p = 0.679$). The Tukey post hoc test showed the medium compliance had significantly higher mean magnitudes of peak resultant rotational acceleration, rotational velocity, and MPS compared to the 45° anvil drop test ($p = 0.029$, $p < 0.001$, $p < 0.001$, respectively). The medium compliance showed higher means for all of the dependent variables when compared to the high compliance pneumatic ram test ($p < 0.05$). The 45° anvil drop test reported significantly higher peak resultant linear acceleration, rotational acceleration and MPS compared to the high compliance test ($p < 0.001$, $p < 0.001$, $p < 0.001$, respectively).

Therefore, the null hypotheses 2, and 4 on the effect of test protocols was rejected. There was no significant difference in peak resultant linear acceleration between the 45° anvil drop and the medium compliance tests ($p = 0.078$). There was also no significant difference in peak resultant rotational velocity between the 45° anvil drop and the high compliance tests ($p = 0.208$).

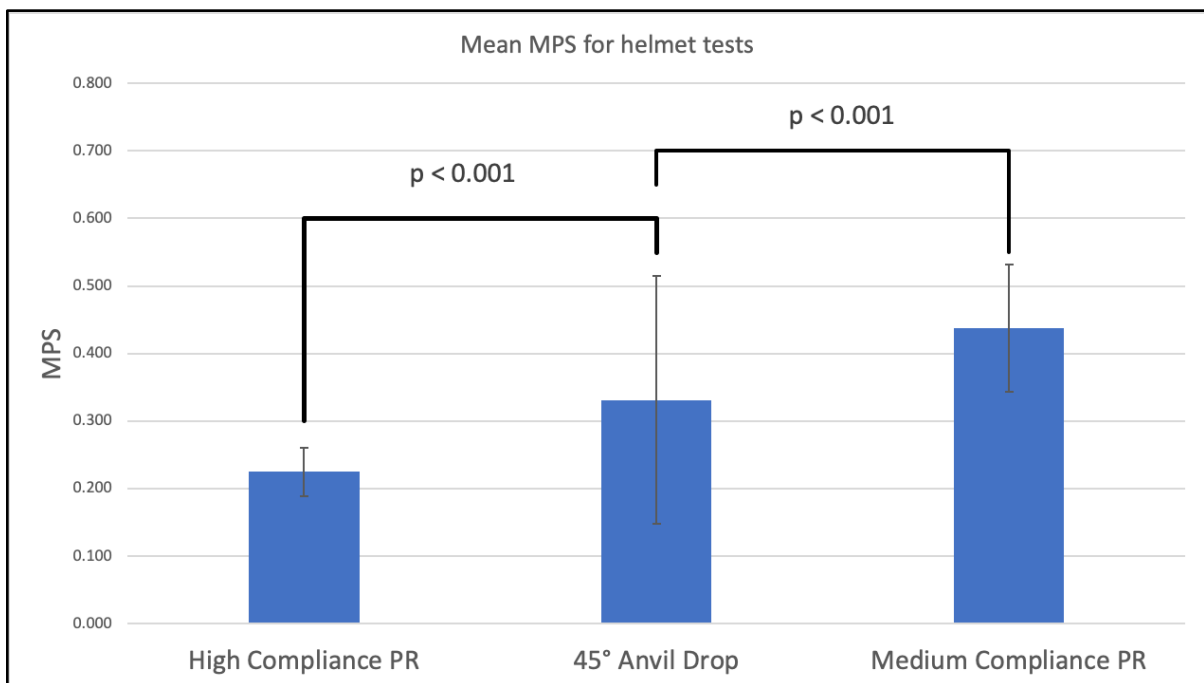
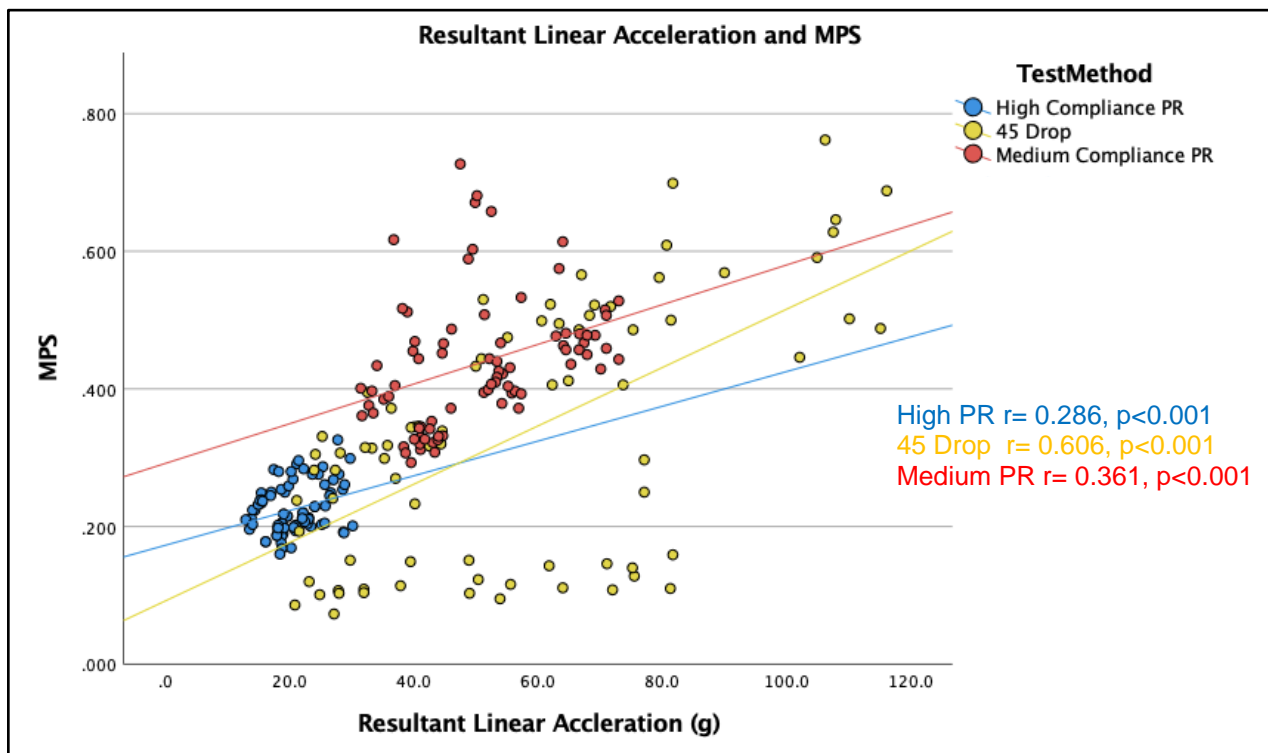


Figure 11. Comparison of means of MPS between the High Compliance, 45° Anvil Drop, and Medium Compliance Helmet Tests.

5.2 Pearson correlation coefficients (r) between dynamic response and MPS

Each dynamic response variable was plotted against MPS to determine the correlations for each of the test protocols. This information was used to determine which dynamic response variable could be used as a tangible performance measure of mitigating brain trauma because although MPS is the ‘gold standard’ in measuring brain trauma in sport, it is a time-consuming variable to calculate.



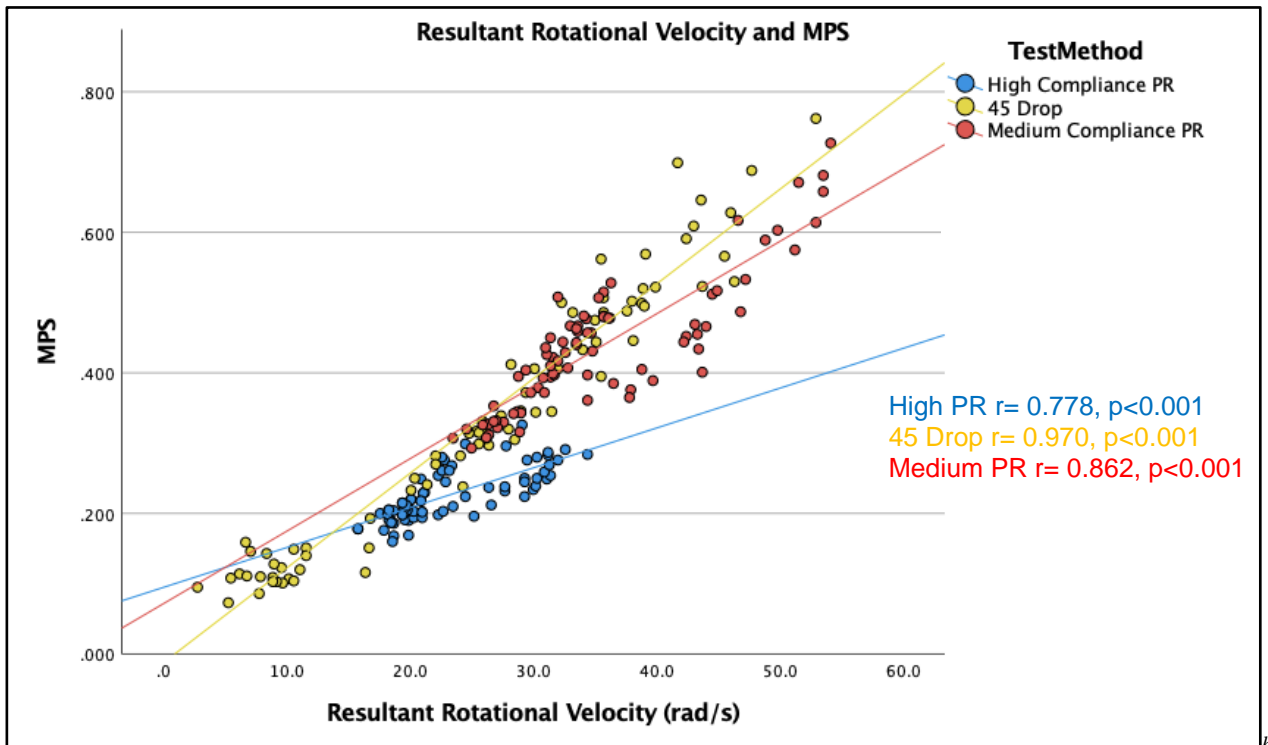
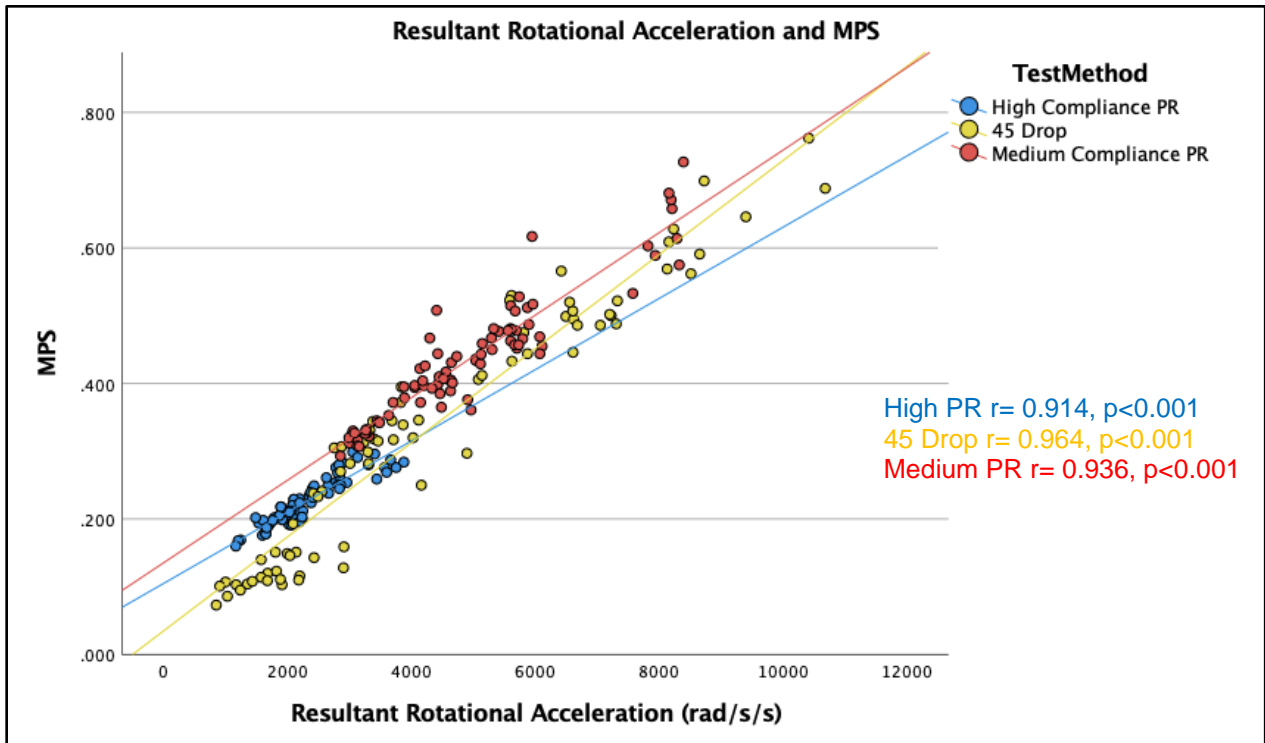


Figure 12. Scatter plots of peak resultant (A) linear Acceleration, (B) rotational Acceleration, and (C) rotational velocity against MPS for the three test protocols.

The variables with the highest correlations with MPS for both the high and medium compliance pneumatic ram tests were resultant rotational acceleration (Figure 12B) with r values of 0.914 and 0.936, respectively. The 45° anvil drop also reported a strong relationship between peak resultant rotational acceleration and MPS ($r=0.964$) however, the strongest relationship was between peak resultant rotational velocity and MPS (Figure 12C., $r=0.970$). There was a weak to moderate relationship between peak resultant linear acceleration and MPS for all of the test protocols.

5.3 Comparisons Within Test Methods

5.3.1 High Compliance Pneumatic Ram Test

Mean dynamic response variables and MPS were compared between the Bare, VN, EPP, Fluid helmet condition for the high compliance pneumatic ram test. The comparisons were made with velocity and locations collapsed (Table 4) followed by comparisons made within each velocity and location.

Table 4. Overall mean comparison for dynamic response and MPS between the Bare, VN, EPP, and Fluid helmet conditions for the High Compliance Pneumatic Ram test. Comparisons were made with a One-Way ANOVA followed by a Tukey post hoc test ($p = 0.05$).

Helmet Type	Resultant			MPS
	Linear Acceleration (g)	Rotational Acceleration (rad/s ²)	Rotational Velocity (rad/s)	
Bare	26.5*** (5.6)	2943*** (643)	30.3*** (5.0)	0.297*** (0.045)
VN	22.4* (fluid) (4.5)	2333 (727)	23.9 (5.4)	0.230 (0.045)
EPP	20.8 (4.2)	2326 (627)	23.4 (4.7)	0.222 (0.028)
FLUID	19.2 (3.7)	2210 (498)	21.7 (4.1)	0.224 (0.034)

* = significant difference ($p < 0.05$) between one other helmet condition; ***= significant difference ($p < 0.05$) between three other helmet conditions

The Bare headform reported significantly higher magnitudes in all of the dependent variables compared to the three helmeted conditions ($p < 0.05$). The only significant differences demonstrated

between the helmet conditions was a higher peak resultant linear acceleration in the VN helmet than the Fluid helmet ($p = 0.048$). To determine the ability of this test to differentiate between helmet designs, a comparison was made for each location and velocity.

Comparisons at 6 m/s

The bare headform produced significantly higher dynamic response and MPS values than all of the helmeted conditions ($p < 0.05$) across all locations. There was one significant difference between helmeted conditions, reported at the Side location. The VN helmet produced significantly less peak resultant linear acceleration and MPS compared to the EPP helmet ($p = 0.002$, $p = 0.009$; respectively) and the Fluid helmet ($p < 0.001$, $p = 0.005$; respectively).

Table 5. Mean (SD) comparison between the Bare headform, the VN, the EPP, and the Fluid helmets for the High Compliance Pneumatic Ram test at 6 m/s. Significant differences between helmeted conditions are highlighted in green.

6 m/s	Test Condition	Resultant			MPS
		Linear Acceleration (g)	Rotational Acceleration (rad/s ²)	Rotational Velocity (rad/s)	
FBPA	Bare	25.4 (0.6)	2331 (35)	26.3 (0.5)	0.277 (0.007)
	VN	18.7 (0.3)	1672 (27)	19.4 (0.6)	0.189 (0.003)
	EPP	20.2 (1.3)	1703 (98)	19.7 (1.6)	0.191 (0.013)
	FLUID	18.4 (0.6)	1775 (114)	19.6 (1.2)	0.201 (0.016)
SIDE	Bare	25.1 (0.2)	2047 (57)	26.6 (1.0)	0.232 (0.005)
	VN	19.2 (1.0)	1207 (39)	19.1 (0.7)	0.166 (0.005)
	EPP	18.5 (0.6)	1545 (62)	21.4 (0.8)	0.198 (0.004)
	FLUID	18.0 (0.5)	1502 (28)	19.4 (0.4)	0.185 (0.006)
RBNA	Bare	17.2 (1.5)	2939 (98)	36.3 (2.6)	0.269 (0.016)
	VN	15.5 (0.0)	2384 (41)	30.4 (0.6)	0.241 (0.008)
	EPP	14.0 (0.5)	2275 (98)	27.0 (2.1)	0.211 (0.014)
	FLUID	14.0 (1.0)	2212 (187)	25.2 (2.2)	0.222 (0.011)

Comparisons at 7.5 m/s

The Fluid helmet reported significant decreases in peak resultant linear acceleration at the FBPA location compared to both the VN helmet ($p = 0.005$) and the EPP helmet ($p = 0.036$). The Fluid helmet also reported significantly decreased peak resultant linear acceleration than the VN helmet at the Side and RBNA location ($p = 0.020, 0.022$; respectively).

The VN helmet produced decreased peak resultant rotational acceleration than both the EPP ($p = 0.045$) and the Fluid ($p = 0.033$) helmets, at the Side location.

Table 6. Mean (SD) comparison between the Bare headform, the VN, the EPP, and the Fluid helmets for the High Compliance Pneumatic Ram test at 7.5 m/s. Significant differences between both of the other helmeted conditions are highlighted in green. Significant differences compared to one other helmet are highlighted in faded green.

7.5 m/s	Test Condition	Resultant			MPS
		Linear Acceleration	Rotational	Rotational Velocity	
		(g)	Acceleration (rad/s ²)	(rad/s)	
FBPA	Bare	26.0 (1.1)	2782 (52)	27.2 (0.2)	0.317 (0.001)
	VN	23.2 (0.8)	2027 (70)	20.2 (0.8)	0.216 (0.012)
	EPP	21.7 (0.8)	2018 (90)	19.3 (1.0)	0.210 (0.011)
	FLUID	18.2 (1.8)	1813 (142)	17.8 (1.8)	0.199 (0.019)
SIDE	Bare	27.3 (1.8)	1963 (133)	20.7 (1.7)	0.206 (0.012)
	VN	22.9 (0.8)	1525 (49)	19.0 (0.6)	0.182 (0.002)
	EPP	20.5 (1.0)	1766 (45)	20.2 (1.4)	0.203 (0.018)
	FLUID	19.0 (1.1)	1783 (102)	18.8 (2.3)	0.196 (0.025)
RBNA	Bare	20.8 (0.9)	3201 (102)	35.3 (1.5)	0.279 (0.008)
	VN	19.7 (1.3)	2970 (158)	31.1 (1.7)	0.265 (0.023)
	EPP	16.5 (1.0)	2787 (105)	29.1 (1.3)	0.244 (0.006)
	FLUID	15.8 (1.7)	2537 (332)	26.8 (4.3)	0.241 (0.040)

Comparisons at 9 m/s

The only differences detected at 9 m/s were at the Side and RBNA locations in peak resultant linear acceleration. Both the EPP and Fluid helmets produced significantly less peak resultant linear acceleration than the VN helmet at the Side ($p = 0.024$, $p = 0.004$; respectively) and RBNA ($p = 0.027$, $p = 0.008$; respectively).

Table 7. Mean (SD) comparison between the Bare headform, the VN, the EPP, and the Fluid helmets for the High Compliance Pneumatic Ram test at 9 m/s. Significant differences between both of the other helmeted conditions are highlighted in green. Significant differences compared to one other helmet are highlighted in faded green.

9 m/s	Test Condition	Resultant			MPS
		Linear Acceleration (g)	Rotational Acceleration (rad/s ²)	Rotational Velocity (rad/s)	
FBPA	Bare	33.7 (1.5)	3614 (131)	30.5 (1.4)	0.389 (0.016)
	VN	28.5 (1.1)	2962 (156)	25.5 (3.3)	0.300 (0.025)
	EPP	28.1 (1.2)	2759 (98)	21.9 (0.9)	0.255 (0.006)
	FLUID	25.4 (1.8)	2559 (294)	21.4 (3.3)	0.243 (0.037)
SIDE	Bare	35.7 (1.0)	2560 (70)	24.9 (0.4)	0.262 (0.004)
	VN	29.2 (0.8)	2085 (76)	18.7 (0.6)	0.195 (0.006)
	EPP	25.6 (0.3)	2187 (7)	20.4 (0.7)	0.213 (0.015)
	FLUID	24.2 (2.0)	2225 (160)	20.5 (2.2)	0.221 (0.022)
RBNA	Bare	28.5 (1.1)	4228 (68)	38.6 (0.8)	0.330 (0.012)
	VN	24.6 (0.9)	3664 (93)	30.9 (1.3)	0.280 (0.006)
	EPP	20.9 (1.2)	3641 (221)	32.2 (1.9)	0.271 (0.013)
	FLUID	20.0 (1.6)	3183 (308)	26.9 (3.9)	0.285 (0.009)

5.3.2 Medium Compliance Pneumatic Ram Test

Mean dynamic response variables and MPS were compared between the Bare, VN, EPP, Fluid helmet condition for the medium compliance pneumatic ram test. The comparisons were made with velocity and locations collapsed (Table 8) followed by comparisons made within each velocity and location.

The Bare headform demonstrated significantly higher magnitudes than the three helmets for peak resultant linear acceleration and rotational velocity ($p < 0.05$). The VN helmet was not significantly different from the Bare headform in terms of peak resultant linear acceleration ($p \geq 0.05$). There were no significant differences reported between any of the conditions for resultant rotational acceleration as well as MPS.

Table 8. Overall mean comparison for dynamic response and MPS between the Bare, VN, EPP, and Fluid helmet conditions for the Medium Compliance Pneumatic Ram test. Comparisons were made with a One-Way ANOVA followed by a Tukey post hoc test ($p = 0.05$).

Helmet Type	Resultant			MPS
	Linear Acceleration (g)	Rotational Acceleration (rad/s ²)	Rotational Velocity (rad/s)	
Bare	64.0** (20.7)	5361 (1791)	42.1*** (7.3)	0.497 (0.127)
VN	53.4 (12.5)	4869 (1483)	35.1 (7.9)	0.428 (0.081)
EPP	50.0 (11.6)	5005 (1434)	35.4 (7.4)	0.428 (0.086)
FLUID	48.8 (11.2)	5033 (1466)	36.1 (8.4)	0.459 (0.112)

= significant difference (p<0.05) between two other helmet conditions; *= significant difference (p < 0.05) between three other helmet conditions.

Comparisons at 6 m/s

At 6 m/s, the Fluid and EPP helmet reported decreased peak resultant linear acceleration than the VN helmet at the RBNA location ($p = 0.016, 0.014$; respectively). The Fluid helmet also produced a significant decrease in peak resultant rotational acceleration compared to the EPP helmet at the RBNA location ($p = 0.019$).

Table 9. Mean (SD) comparison between the Bare headform, the VN, the EPP, and the Fluid helmets for the Medium Compliance Pneumatic Ram test at 6 m/s. Significant differences between both of the other helmeted conditions are highlighted in green. Significant differences compared to one other helmet are highlighted in faded green.

		Resultant			
6 m/s	Test Condition	Linear Acceleration (g)	Rotational Acceleration (rad/s ²)	Rotational Velocity (rad/s)	MPS
FBPA	Bare	46.0 (3.8)	3841 (270)	34.3 (2.7)	0.434 (0.033)
	VN	41.1 (0.1)	3017 (36)	26.2 (1.5)	0.321 (0.009)
	EPP	40.5 (2.6)	3040 (159)	26.7 (2.0)	0.306 (0.012)
	FLUID	41.7 (1.5)	3228 (127)	26.5 (0.5)	0.325 (0.003)
SIDE	Bare	48.4 (1.3)	3284 (87)	32.4 (1.4)	0.336 (0.003)
	VN	44.2 (0.4)	3265 (8)	26.6 (0.6)	0.330 (0.003)
	EPP	42.7 (2.9)	3542 (143)	29.2 (0.6)	0.353 (0.016)
	FLUID	41.4 (2.3)	3426 (244)	26.2 (2.5)	0.334 (0.024)
RBNA	Bare	38.3 (0.6)	4182 (197)	41.2 (0.8)	0.384 (0.007)
	VN	36.1 (0.9)	4579 (100)	38.3 (1.7)	0.393 (0.011)
	EPP	32.9 (1.2)	4971 (67)	38.6 (4.5)	0.390 (0.039)
	FLUID	32.8 (1.1)	4448 (236)	38.6 (4.7)	0.388 (0.020)

Comparisons at 7.5 m/s

When increasing velocity to 7.5 m/s, the Fluid helmet reported a decrease in peak resultant linear acceleration compared to the VN helmet ($p = 0.005$) at the Side location and a decrease compared to both the VN ($p < 0.001$) and EPP ($p = 0.023$) helmets at the RBNA location. In terms of peak resultant rotational acceleration, the VN helmet reported a significant decrease compared to both the EPP ($p = 0.033$) and Fluid ($p = 0.031$) helmets at the Side location. At the RBNA location, both the VN and Fluid helmets demonstrated a significant decrease in peak resultant rotational acceleration compared to the EPP helmet ($p = 0.001$, $p = 0.041$; respectively). There was also a significant decrease in MPS in the EPP helmet compared to the Fluid helmet at the RBNA location ($p = 0.032$).

Table 10. Mean (SD) comparison between the Bare headform, the VN, the EPP, and the Fluid helmets for the Medium Compliance Pneumatic Ram test at 7.5 m/s. Significant differences between both of the other helmeted conditions are highlighted in green. Significant differences compared to one other helmet are highlighted in faded green.

7.5 m/s	Test Condition	Resultant			MPS
		Linear Acceleration (g)	Rotational Acceleration (rad/s ²)	Rotational Velocity (rad/s)	
FBPA	Bare	62.2 (3.6)	5043 (246)	39.6 (1.5)	0.551 (0.027)
	VN	53.1 (1.6)	4080 (178)	30.5 (1.5)	0.414 (0.017)
	EPP	55.4 (1.1)	4000 (96)	31.2 (0.7)	0.390 (0.010)
	FLUID	52.7 (1.1)	4384 (75)	32.5 (1.0)	0.437 (0.035)
SIDE	Bare	66.9 (0.4)	3912 (81)	36.7 (0.8)	0.428 (0.001)
	VN	56.5 (1.1)	4221 (97)	30.4 (0.8)	0.390 (0.016)
	EPP	54.0 (1.3)	4551 (99)	32.7 (1.8)	0.419 (0.011)
	FLUID	52.4 (1.0)	4554 (165)	32.8 (0.8)	0.452 (0.052)
RBNA	Bare	50.2 (0.4)	5843 (33)	48.9 (1.3)	0.479 (0.014)
	VN	45.2 (0.8)	5799 (97)	44.4 (2.2)	0.468 (0.018)
	EPP	40.3 (0.5)	6085 (21)	42.9 (0.6)	0.456 (0.013)
	FLUID	38.0 (1.1)	5928 (48)	45.3 (1.1)	0.549 (0.059)

Comparisons at 9 m/s

The Fluid and EPP helmets showed a decrease in peak linear acceleration compared to the VN helmet at the RBNA location ($p = 0.003$, $p = 0.002$; respectively). The VN reported a decrease in peak resultant rotational acceleration at the Side location compared to both the EPP ($p = 0.002$) and Fluid ($p = 0.002$) helmets. The VN helmet also showed a decrease in MPS compared to the Fluid helmet ($p = 0.010$) at the RBNA location.

Table 11. Mean (SD) comparison between the Bare headform, the VN, the EPP, and the Fluid helmets for the Medium Compliance Pneumatic Ram test at 9 m/s. Significant differences between both of the other helmeted conditions are highlighted in green. Significant differences compared to one other helmet are highlighted in faded green.

9 m/s	Test Condition	Resultant			MPS
		Linear Acceleration	Rotational	Rotational	
		(g)	Acceleration	Velocity	
		(g)	(rad/s ²)	(rad/s)	
FBPA	Bare	94.6	8424	51.4	0.783
		(6.5)	(429)	(3.8)	(0.048)
	VN	71.6	5674	35.8	0.517
		(1.2)	(70)	(0.5)	(0.011)
	EPP	66.9	5211	31.8	0.451
		(1.4)	(150)	(1.1)	(0.016)
	FLUID	64.9	5446	34.7	0.480
		(2.2)	(138)	(0.9)	(0.002)
SIDE	Bare	99.5	5599	41.5	0.516
		(2.8)	(193)	(0.9)	(0.014)
	VN	71.4	5128	33.2	0.444
		(1.5)	(15)	(0.6)	(0.015)
	EPP	66.6	5654	34.8	0.466
		(2.6)	(47)	(1.4)	(0.011)
	FLUID	66.4	5636	35.4	0.472
		(1.7)	(88)	(0.9)	(0.013)
RBNA	Bare	69.9	8118	52.7	0.561
		(2.6)	(253)	(1.8)	(0.024)
	VN	61.6	8062	50.4	0.574
		(3.7)	(423)	(2.9)	(0.041)
	EPP	50.3	7987	50.7	0.617
		(2.0)	(199)	(2.5)	(0.036)
	FLUID	49.2	8247	53.0	0.693
		(1.5)	(126)	(1.4)	(0.030)

5.3.3 45° Anvil Drop Test

Mean dynamic response variables and MPS were compared between the Bare, VN, EPP, Fluid helmet conditions for the 45° anvil drop test. The comparisons were made with velocity and locations collapsed (Table 11) followed by comparisons made within each velocity and location.

Table 12. Overall mean comparison for dynamic response and MPS between the Bare, VN, EPP, and Fluid helmet conditions for the 45° Anvil Drop test. Comparisons were made with a One-Way ANOVA followed by a Tukey post hoc test ($p = 0.05$).

Helmet Type	Resultant			MPS
	Linear Acceleration (g)	Rotational Acceleration (rad/s ²)	Rotational Velocity (rad/s)	
Bare	208.4***	15936***	26.7	0.455
	(72.7)	(6546)	(5.7)	(0.128)
VN	53.6	4088	26.6	0.335
	(27.2)	(2728)	(15.2)	(0.203)
EPP	60.7	4800	25.2	0.357
	(25.2)	(2713)	(13.6)	(0.196)
FLUID	55.2	3932	24.6	0.302
	(26.5)	(2143)	(10.6)	(0.148)

*** significant difference ($p < 0.05$) between the three other helmet conditions.

The Bare headform reported significantly higher resultant and dominant linear and rotational acceleration compared to the helmet conditions ($p < 0.05$). There were no significant differences between any of the conditions for resultant velocity as well as MPS.

Comparisons at 3 m/s

The 45° Anvil Drop test detected a significant decrease in peak resultant rotational acceleration for the Fluid helmet compared to the EPP helmet condition ($p = 0.014$) at the RB location. The Fluid helmet also reported significant decreases in peak resultant rotational velocity and MPS compared to both the VN ($p = 0.003$, $p = 0.010$; respectively) and EPP ($p = 0.004$, $p = 0.002$) helmets at the RB location.

Table 13. Mean (SD) comparison between the Bare headform, the VN, the EPP, and the Fluid helmets for the 45° Anvil Drop test at 3 m/s. Significant differences between both of the other helmeted conditions are highlighted in green. Significant differences compared to one other helmet are highlighted in faded green.

		Resultant			
3 m/s	Test Condition				MPS
		Linear Acceleration (g)	Rotational Acceleration (rad/s ²)	Rotational Velocity (rad/s)	
SIDE	Bare	155.4 (7.7)	18017 (824)	27.0 (0.5)	0.526 (0.036)
	VN	33.1 (4.3)	3192 (279)	26.0 (0.3)	0.308 (0.010)
	EPP	38.0 (5.7)	3698 (411)	27.4 (2.4)	0.335 (0.032)
	FLUID	36.5 (4.0)	2939 (490)	22.6 (2.8)	0.273 (0.041)
RB	Bare	150.3 (12.8)	11643 (875)	23.8 (0.2)	0.362 (0.011)
	VN	24.1 (2.9)	2577 (169)	24.7 (3.6)	0.261 (0.038)
	EPP	25.6 (1.7)	3218 (179)	24.0 (1.9)	0.298 (0.028)
	FLUID	24.8 (3.2)	1334 (658)	12.2 (4.0)	0.134 (0.051)
REAR	Bare	168.5 (9.7)	8231 (1399)	20.8 (2.4)	0.297 (0.017)
	VN	24.0 (3.6)	1296 (342)	9.4 (1.7)	0.103 (0.017)
	EPP	36.5 (4.0)	1751 (220)	8.6 (2.2)	0.124 (0.022)
	FLUID	29.7 (2.4)	1338 (478)	10.9 (5.7)	0.109 (0.039)

Comparisons at 4.5 m/s

At 4.5 m/s, there were significant differences detected at all locations. At the Side location, the Fluid reported significant decreases in peak resultant linear rotational acceleration compared to the EPP helmet ($p = 0.031$); peak resultant rotational acceleration than both the VN ($p = 0.014$) and EPP ($p = 0.001$) helmets; peak resultant rotational velocity than the VN helmet ($p = 0.009$); and MPS compared to both the VN ($p = 0.008$) and EPP helmets ($p = 0.005$). At the RB location, the VN helmet reported a significant decrease in peak resultant linear acceleration compared to the EPP helmet ($p = 0.021$). The Fluid helmet reported a significant decrease in peak resultant rotational velocity compared to the VN helmet condition ($p = 0.024$). At the Rear location, both the VN and Fluid helmets reported significantly less peak resultant linear acceleration compared to the EPP helmet ($p = 0.019$, $p = 0.039$; respectively).

Table 14. Mean (SD) comparison between the Bare headform, the VN, the EPP, and the Fluid helmets for the 45° Anvil Drop test at 4.5 m/s. Significant differences between both of the other helmeted conditions are highlighted in green. Significant differences compared to one other helmet are highlighted in faded green.

4.5 m/s	Test Condition	Resultant			MPS
		Linear	Rotational	Rotational	
		Acceleration (g)	Acceleration (rad/s ²)	Velocity (rad/s)	
SIDE	Bare	308.4	25059	33.7	0.627
		////	////	////	////
	VN	68.9	6613	36.8	0.504
		(2.6)	(63)	(1.8)	(0.017)
	EPP	78.7	7596	33.7	0.516
		(3.1)	(799)	(1.7)	(0.040)
FLUID		67.0	4939	30.1	0.408
		(6.0)	(298)	(1.9)	(0.003)
RB	Bare	279.3	23940	34.6	0.580
		(7.6)	(2921)	(3.5)	(0.090)
	VN	37.4	3634	32.4	0.361
		(4.2)	(235)	(2.8)	(0.029)
	EPP	52.0	5771	34.7	0.451
		(2.7)	(131)	(0.6)	(0.022)
FLUID		42.6	3899	27.3	0.334
		(1.9)	(206)	(1.8)	(0.015)
REAR	Bare	348.2	12551	22.3	0.456
		////	////	////	////
	VN	51.1	1660	7.1	0.107
		(2.5)	(365)	(3.7)	(0.014)
	EPP	65.9	1917	6.9	0.121
		(5.4)	(499)	(1.5)	(0.019)
FLUID		52.3	2170	14.0	0.134
		(3.7)	(609)	(4.2)	(0.055)

Comparisons at 6 m/s

At the Side location, the Fluid helmet produced a significant decrease in peak resultant rotational acceleration and velocity as well as MPS, compared to the VN helmet condition ($p = 0.032$, $p = 0.005$, $p = 0.007$; respectively). At the RB location, the VN and Fluid helmet reported significantly less peak resultant linear acceleration compared to the EPP helmet condition ($p = 0.007$, $p = 0.017$; respectively). The VN and Fluid also showed a decrease in peak resultant rotational acceleration compared to the EPP helmet condition ($p < 0.001$, $p = 0.011$; respectively). There was a significant decrease in peak resultant rotational velocity for both the EPP and Fluid helmets compared to the VN helmet condition ($p = 0.035$, $p = 0.005$; respectively). The Fluid helmet also showed a decrease in MPS compared to the EPP helmet ($p = 0.028$). Finally, for the Rear location, the VN helmet demonstrated a significant decrease in peak resultant rotational acceleration and velocity, and MPS compared to the Fluid helmet ($p = 0.027$, $p = 0.010$, $p = 0.009$; respectively). The VN reported a significant decrease in peak resultant linear acceleration compared to the EPP helmet ($p = 0.019$). The EPP reported significant decreases in peak resultant rotational velocity and MPS compared to the Fluid helmet ($p = 0.009$, $p = 0.011$; respectively).

Table 15. Mean (SD) comparison between the VN, the EPP, and the Fluid helmets for the 45° Anvil Drop test at 6 m/s. Significant differences between both of the other helmeted conditions are highlighted in green. Significant differences compared to one other helmet are highlighted in faded green.

6 m/s	Test Condition	Resultant			MPS
		Linear Acceleration (g)	Rotational Acceleration (rad/s ²)	Rotational Velocity (rad/s)	
SIDE	VN	109.9	9775	48.9	0.693
		(5.4)	(1342)	(3.6)	(0.067)
	EPP	106.4	9025	43.0	0.619
		(2.1)	(527)	(0.8)	(0.039)
	FLUID	109.1	7039	37.9	0.479
		(6.6)	(376)	(0.3)	(0.029)
RB	VN	60.1	5874	45.2	0.540
		(8.1)	(473)	(1.3)	(0.023)
	EPP	84.1	8337	41.3	0.626
		(5.1)	(337)	(2.0)	(0.067)
	FLUID	64.4	6812	39.2	0.505
		(4.3)	(449)	(0.6)	(0.015)
REAR	VN	73.9	2174	9.2	0.138
		(2.5)	(674)	(2.3)	(0.009)
	EPP	81.5	2547	7.3	0.135
		(0.3)	(516)	(0.8)	(0.035)
	FLUID	77.1	4529	23.4	0.274
		(3.0)	(1053)	(3.8)	(0.024)

*It should be noted that the bare headform condition was not included at 6 m/s to prevent the risk of damaging the equipment.

Chapter 6: Discussion

This thesis compared three rotational test methods to determine if they produced different dynamic response and MPS values, this thesis also evaluated the ability of the three tests to differentiate between helmet designs. The following sections will discuss the helmet tests in this thesis and their ability to evaluate helmet protection.

6.1 Medium and High Compliance Pneumatic Ram Test and 45° Anvil Drop Test

Peak resultant rotational acceleration as well as MPS were significantly greater for the Medium Compliance pneumatic ram test followed by the 45° Anvil Drop test and finally the High Compliance Pneumatic Ram (PR) test. These results are supported in the literature on the effects of impact parameters on dynamic head response and MPS. The high compliance test demonstrated the lowest dynamic response and MPS values which can be attributed to the longer impact duration (average of 25 ms) compared to the other tests (de Grau et al., 2019). When the compliance of the impactor increases, the foam compresses and less energy is transferred to the helmeted headform. The dynamic response and MPS magnitude that were observed are supported by previous literature on this test protocol (Meehan MSc Thesis, 2019; de Grau et al., 2019, 2020). There was no significant difference in resultant rotational velocity between the high compliance test and the 45° anvil drop which was influenced by high variances in the angled drop test.

The 45° anvil drop test produced the second highest values overall for dynamic response and MPS with significantly lower resultant rotational acceleration and rotational velocity, and MPS compared to the medium compliance test. There was no difference in peak resultant linear acceleration between the two test methods. The high variance in the 45° anvil drop test may have resulted in no significant differences in those areas when velocity and locations were collapsed (Meehan Msc Thesis, 2019). The

higher magnitudes observed in the medium compliance test compared to the angled drop test was a result of the higher velocity range. The highest velocity in the angled drop test protocol was 6 m/s while in the ram tests the velocities ranged from 6 m/s to 9 m/s. At 6 m/s, the medium compliance test produced lower dynamic response and MPS than the 45° anvil drop test at 6 m/s, which is a result of the lower compliant steel anvil. Although the 45° anvil drop test and the medium compliance test had similar average durations of impact (15 ms), velocity was more influential on dynamic response variables and MPS which is consistent with previous research investigating the influence of impact parameters (Ouer et al., 2018).

6.2 Dynamic Response Correlations with MPS For Each Test Protocol

For both compliance levels of the Pneumatic Ram test, resultant rotational acceleration was strongly correlated with MPS ($R^2=0.827$, $R^2=0.875$, respectively). This is consistent with reported findings investigating dependent variables as predictors of MPS using the same test protocol (Meehan MSc Thesis, 2019). Compliant collision impacts in ice hockey have also reported strong correlations for rotational acceleration and MPS (Post et al., 2011).

Resultant rotational velocity had the highest correlation with MPS for the 45° Anvil Drop test ($R^2=0.941$). Meehan (Msc Thesis, 2019) reported similar results when determining the predictive abilities of dynamic response measures for MPS for the same test.

6.3 High Compliance Pneumatic Ram Test Sensitivity

To establish the ability of the helmet test protocols to distinguish between different helmet designs, the data was analyzed by each location for each velocity. Overall, the high compliance test detected 8 significant differences between at least two of the helmets for all the impact conditions. When analyzing peak resultant rotational acceleration (strongest relationship with MPS), the test detected 2 significant

differences. The differences were detected at 6 and 7.5 m/s impact velocities for the Side location. At 9m/s, impact velocity the helmets reported differences in peak resultant linear acceleration with no differences in rotational metrics or MPS. At this velocity, the high compliance impactor compresses decreasing the helmets abilities to mitigate rotational motion (de Grau et al., 2020). Decreasing the compliance would activate the helmets protective mechanism, however, the mean duration of impact for the high compliance test is representative of the durations seen in real world shoulder-to-head impacts at 25 ms (Meehan MSc Thesis, 2019). This information supports the need for hockey helmets to be designed and tested under high compliance conditions to improve their protective abilities for collisions between players which account for 88% of concussions in professional ice hockey (Hutchinson et al., 2015).

6.4 Medium Compliance Pneumatic Ram Test Sensitivity

The Medium Compliance test resulted in 10 significant differences between at least two helmets when all of the conditions were analyzed. Similar to the high compliance test, resultant rotational acceleration had the highest correlation with MPS. When each impact condition was considered, 4 significant differences were identified for resultant rotational acceleration between at least two helmets. These included the RBNA location at 6 m/s impact velocity, the Side and RBNA locations at 7.5 m/s impact velocity and Side location at 9 m/s. These results demonstrate that decreasing the compliance for the Pneumatic Ram test resulted in a more sensitive test in terms of detecting performance differences between helmets. There was less compression of the impactor due to lower compliance and thus the helmets protective abilities were better observed compared to the higher compliance impactor. The RBNA and the Side were the locations that detected the significant differences between the helmets with the highest number of differences identified at 7.5 m/s meaning the locations at this velocity are the most sensitive to helmet design differences.

While the medium compliance test proved to be more sensitive than the high compliance test, it should be noted that the duration of impact for this test (15 ms) is shorter than what is reported for shoulder-to-head collisions in professional ice hockey (20+ ms). This means it is not as representative of the duration of real-world concussive injuries resulting from the shoulder contacting the head. (Post et al., 2019; Meehan MSc Thesis, 2019).

6.5 45° Anvil Drop Test

There were 21 significant differences detected for the dependent variables between at least two helmets for the conditions analyzed. Using peak resultant rotational velocity as a performance measure, the test identified 6 significant differences between the helmets. These were observed at 3 m/s at the RB location, at 4.5 m/s for the Side and RB locations, and at 6 m/s across all three locations. While the majority of differences were detected at 6 m/s, Meehan and colleagues (2019) proposed that the 45° anvil drop test at this velocity produces magnitudes of dynamic response variables and MPS that are above what is reported in real world head-to-boards concussive impacts. The most sensitive conditions which fall within ranges of dynamic response of head-to-board impacts in professional ice hockey would be at 4.5 m/s at the Side and RB locations.

The 45° anvil drop test was the most sensitive test when compared to the high/medium compliance pneumatic ram tests; however, it is a more variant test due to the rigid surface of the steel anvil. It would be beneficial to investigate a combined 45° Anvil Drop test and a Pneumatic Ram test with a compliant impactor cap that falls between the medium and high compliance impactors (20 ms).

Chapter 7: Conclusion

The objectives of this thesis were to 1) compare three rotational test methods using peak dynamic response and peak strain and 2) to describe the ability of the tests to detect differences in helmet performance. This thesis demonstrated that when the High/Medium Compliance Pneumatic Ram tests and the 45° Anvil Drop test were compared, they produced unique dynamic and brain tissue response (MPS). To determine the performance measures of interest, the High and Medium Compliance Pneumatic Ram tests both reported strong correlations between peak resultant rotational acceleration and MPS while the 45° Anvil Drop test reported peak resultant rotational velocity to have the strongest correlation with MPS. While these tests have been determined to be unique to one another, their ability to measure helmet performance were investigated.

Using peak resultant rotational acceleration as a performance measure, the High Compliance Pneumatic Ram test was observed to be the least sensitive to detect differences in helmet design with 2 impact conditions where performance differences could be seen. Increasing compliance to the Medium Compliance Pneumatic Ram test, there were 4 impact conditions where differences existed between the helmets. Using peak resultant velocity as a performance measure, the 45° Anvil Drop Test reported 6 impact conditions demonstrating differences between the helmet designs. As compliance was decreased, the sensitivity of the test increased.

Ice hockey helmets need to be tested under conditions that induce rotation and represent how concussions most commonly occur in ice hockey and sensitive enough to measure differences between helmet performance. Using both the 45° Anvil Drop test and a Pneumatic Ram test with a compliance that lies between the medium and high compliance impactor caps could solve this issue. The information from this thesis will inform the development of rotational testing standards of ice hockey helmets as well as inform helmet manufacturers in designing helmets that can better manage higher compliance impacts.

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Appendix A: Summary of current helmet standards tests

Table A-1: Summary of test equipment, impact parameters, and pass/fail criteria for current ice hockey helmet standard tests

	CSA Z262.1-15	ASTM F1045-16	ISO 10256-2:2016
EQUIPMENT	Monorail	Monorail or Twin-wire	Monorail
HEADFORM	CEN EN 960 magnesium headform/uniaxial accelerometer	CEN EN 960 magnesium headform/uniaxial accelerometer	CEN EN 960 magnesium headform/uniaxial accelerometer/triaxial accelerometer
VELOCITY	4.5 m/s	4.5 m/s	4.5 m/s
ANVIL	25 mm 60 +/- 5 Shore A MEP Pad	25 mm 60 +/- 5 Shore A MEP Pad	25 mm 60 +/- 5 Shore A MEP Pad
LOCATIONS	Crown, Front, Frontboss, Side, Rearboss, Rear	Crown, Front, Frontboss, Side, Rearboss, Rear	Crown, Front, Frontboss, Side, Rearboss, Rear
PASS/FAIL	275g	275g	275g