

Risk of head injury associated with distinct head impact events
in elite women's hockey

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Abstract

Head injuries are a major health concern for sport participants as 90% of emergency department visits for sport-related brain injuries are concussion related (Canadian Institute for Health Information, 2016). Recently, reports have shown a higher incidence of sport-related concussion in female athletes compared to males (Agel et al., 2007). Few studies have described the events by which concussions occur in women's hockey (Delaney et al., 2014, Brainard et al., 2012; Wilcox et al., 2014), however a biomechanical analysis of the risk of concussion has not yet been conducted. Therefore, the purpose of this study was to identify the riskiest concussive events in elite women's hockey and characterize these events through reconstructions to identify the associated levels of peak linear and angular acceleration and strain from finite element analysis.

44 head impact events were gathered from elite women's hockey game video and analyzed for impact event, location and velocity. In total, 27 distinct events based on impact event, location and velocity were reconstructed using a hybrid III headform and various testing setups to obtain dynamic response and brain tissue response. A three-way Multivariate Analysis of Variance (MANOVA) was conducted to determine the influence of event, location and velocity. The results of this study show that head-to-ice impacts resulted in significantly higher responses compared to shoulder-to-head collisions and head-to boards impacts however, shoulder and boards impacts were more frequent. All events produced responses comparable to proposed concussion threshold values (Zhang et al., 2004). This research demonstrates the importance of considering the event, the impact characteristics, the magnitude of

response, and the frequency of these impacts when attempting to capture the short and long term risks of brain trauma in women's hockey.

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1 CHAPTER 1: INTRODUCTION

1.1 Background

Head injuries are a major public health concern for sport participants. According to the Canadian Institute for Health Information, 9 out of every 10 emergency department visits for sport-related brain injuries are concussion related (Canadian Institute for Health Information, 2016). Concussion is also known as mild traumatic brain injury (mTBI) and is the most common form of traumatic brain injury. A concussion occurs when a sudden impact to the head creates a high acceleration or deceleration of the brain inside the skull. Participants of contact sports, such as ice hockey, experience a higher risk of head injury, due to increased exposure to head impacts in addition to players moving at fast speeds (Delaney et al., 2014). Recently, reports have indicated a higher incidence of sport-related concussion in female athletes compared to their male counterparts (Agel et al., 2007; Dvorak et al., 2007; Gessel et al., 2007). In addition to concussion incidence, it has been reported that females present with more severe symptoms when compared to males. This includes greater decline from baseline scores in simple and complex reaction time, cognitive impairment and visual memory tasks (Broshek et al., 2005; Covassin et al., 2007; Dick, 2009). Concussion recovery typically lasts between 7-10 days; however, in more severe cases, concussion can result in post-concussion syndrome (PCS) where symptoms persist for months and even years (McCrory et al., 2013; Marshall et al., 2012). More recent research suggests that becoming symptom-free is a longer

process for women than men and that PCS is more commonly diagnosed in women, (Spinosa et al., 2010; Preiss-Farzanegan et al., 2009).

Women's ice hockey is a high velocity sport, which includes many situations that involve impacts to the head. The NCAA Injury Surveillance System (ISS) reported women's hockey to have the highest rate of concussions (0.91/1000 A-Es) of 16 males and female collegiate-level contact sports (Hootman et al., 2007). However, the primary difference between men's hockey and women's hockey is the absence of body checking in the women's game. This means that intentional body checking results in the offending player serving at least a two-minute penalty. Although body checking is illegal in women's hockey, contact between players still exists. It has been reported that head impact events occur approximately half as frequently in women's hockey as in men's hockey, where body checking is legal (Brainard et al., 2012; Wilcox et al., 2014). As a result, it is understood that the higher incidence of concussion in women's hockey when compared to men's hockey is not necessarily a result of increased head impact exposure.

As female hockey players increase in age, they also increase in speed and size, meaning collisions between two players or collisions between players and hard surfaces can harbour more energy than with younger athletes (Kneightly et al., 2013). Further, researchers have found that athletes competing in the highest skill level within an age category have a higher risk of injury than lower skill levels (Kneightly et al., 2013). Recent professionalization of women's hockey leagues in North America, i.e., the Canadian Women's Hockey League, and National Women's Hockey League, means that it is important to understand the risk of concussion

associated with participation at this level. More specifically, it is necessary to identify the most common head impact events leading to concussion and understand how the impact characteristics of these on-ice situations contribute to risk. The purpose of this thesis was to characterize the distinct head impact events and the associated dynamic and brain tissue response specific to elite women's hockey using reconstructed head impact events.

1.2 Research Questions

1. What are the dynamic response and brain tissue response characteristics associated with head impact events in elite women's hockey?
2. How do the impact parameters that describe head impact events influence dynamic response and brain tissue response?

1.3 Objectives

1. To describe the three distinct head impact events that commonly lead to concussion in elite women's hockey
2. To compare peak linear acceleration for the three distinct head impact events that commonly lead to concussion in women's hockey
3. To compare peak angular acceleration for the three distinct head impact events that commonly lead to concussion in women's hockey
4. To compare maximum principal strain for the three distinct head impact events that commonly lead to concussion in women's hockey

1.4 Variables

1.4.1 *Independent Variables*

1. Head Impact Event
 - a. Shoulder-to-head
 - b. Head-to-ice
 - c. Head-to-boards
2. Location: Three locations per event represent high, medium and low frequency
 - a. Shoulder-to-head
 - i. High: R1/2D Non-centric
 - ii. Medium: R1/2D Centric
 - iii. Low: R3D
 - b. Head-to-ice
 - i. High: Back C
 - ii. Medium: R1/2 C
 - iii. Low: R3C
 - c. Head-to-boards
 - i. High: R3B
 - ii. Medium: R1/2C
 - iii. Low: Back C
3. Velocity: Three velocities per event represent average velocity minus 1 m/s, average velocity, and average velocity plus 1 m/s
 - a. Shoulder-to-head

- i. Average velocity minus 1 m/s: 3.6 m/s
 - ii. Average velocity: 4.6 m/s
 - iii. Average velocity plus 1 m/s: 5.6 m/s
- b. Head-to-ice
 - i. Average velocity minus 1 m/s: 3.8 m/s
 - ii. Average velocity: 4.8 m/s
 - iii. Average velocity plus 1 m/s: 5.8 m/s
- c. Head-to-boards
 - i. Average velocity minus 1 m/s: 2.2 m/s
 - ii. Average velocity: 3.2 m/s
 - iii. Average velocity plus 1 m/s: 4.2 m/s

1.4.2 Dependent Variables

- 1. Dynamic Response
 - a. Peak linear acceleration
 - b. Peak angular acceleration
- 2. Brain Tissue Deformation
 - a. Maximum principal strain

1.5 Hypotheses

- 1. It was hypothesized that the head impact events of shoulder-to-head, head-to-boards, and head-to-ice will each result in different peak linear acceleration, peak angular acceleration and maximum principal strain.

2. It was hypothesized that impact location will result in differences in peak linear acceleration, peak angular acceleration and maximum principal strain.
3. It was hypothesized that changes in impact velocity will result in significant increases to peak linear acceleration, peak angular acceleration and maximum principal strain

1.5.1 Null Hypotheses

1. Head impact event will have no effect on peak linear acceleration
2. Head impact event will have no effect on peak angular acceleration
3. Head impact event will have no effect on maximum principal strain
4. Impact location will have no effect on peak linear acceleration
5. Impact location will have no effect on peak angular acceleration
6. Impact location will have no effect on maximum principal strain
7. Impact velocity will have no effect on peak linear acceleration
8. Impact velocity will have no effect on peak angular acceleration
9. Impact velocity will have no effect on maximum principal strain

1.6 Significance

The value of this research includes the importance of understanding the biomechanical response characteristics of an impacted head to represent head impact events specific to women's hockey. Elite women's hockey (NCAA) reports the highest athlete exposures to concussion amongst female and male contact sports and it is important to understand the mechanics of how women are receiving these

injuries (Hootman et al., 2007). Some research has been done to investigate why women might be at a higher risk of head injury in hockey; however, there is still no definitive explanation that describes the difference between men's and women's concussion incidence (Brook et al., 2016). It is necessary to understand if the head impact biomechanics and corresponding response of impacts in women's hockey should be considered as an important contributor to high concussion incidence. Characteristics of the conditions that describe an impact event are related to head dynamic response; therefore changing impact locations and increasing impact velocities will change the level or risk associated with the impact event. The head dynamics and brain tissue response values of distinct head impact events that commonly lead to injury will be compared with known concussion risk thresholds. This, in addition to an analysis of variable location and velocity, will provide an understanding of the riskiest impact events and their conditions in elite women's hockey. The identification of high-risk scenarios can give leaders and advocates in the women's hockey community information to guide safety improvements. Furthermore, this information can promote rule changes and safety protocols that can improve the safety of the sport and its players.

1.7 Limitations

1. Hybrid III headforms are composed of steel and vinyl and therefore are not biofidelic and do not respond identically to the human head under all conditions of impact

2. Maximum principal strain does represent peak strain throughout the cerebrum however; it does not provide the direction of strain, which may be an important factor in concussion.

1.8 Delimitations

1. The velocities and locations of head impact events in elite women's hockey which are used to inform the testing protocol in this study are observed from a small sample of head impact events and may not represent every possible head impact event scenario
2. The University College of Dublin Brain Trauma Model was developed from adult male CT data of cadavers and does not fully represent female geometry but will be scaled to the size of the 5th-percentile hybrid III headform.
3. The University College of Dublin Brain Trauma Model was not designed for the prediction of head injury, however it can be used to help inform relationships and trends between independent variables.
4. The 5th-percentile Hybrid III headform that will be used for this study is modeled to represent a small female head size. As such, the size of this headform does not necessarily represent head size for all elite women's hockey players.
5. A pneumatic linear impactor was used to represent shoulder-to-head impact conditions seen in elite women's hockey. The system consists of a pneumatically accelerated impacting arm encased in a standing frame (length 1.28 ± 0.01 m; mass 13.1 ± 0.1 kg). The mass of the impacting arm

does not represent the average striking mass of an elite women's hockey player (10.5kg). Previous studies have indicated that increasing impact mass above 10kg does not have a significant effect on dynamic response (Karton et al., 2013).

2 CHAPTER 2: REVIEW OF LITERATURE

2.1 Head Injury

Brain injury occurs when a sudden impact to the head creates deformation, acceleration or deceleration of the skull and brain (Gurdjian, et al., 1964). The most common form of traumatic brain injury in hockey is a form of mild traumatic brain injury (mTBI) known as concussion (McCrory et al, 2016). In the past, the terms concussion and mTBI have been used interchangeably to describe the same injury. Recently, the International Conference of Concussion in Sport (2016) described sport related concussion (SRC) as a traumatic brain injury induced by biomechanical forces that can result in the rapid onset of short-lived impairment of neurological function (McCrory et al., 2016). This injury is distinguished from focal and diffuse injuries and described as a functional injury not a structural injury. In the majority of concussion cases (80-90%) symptoms resolve within 7-10 days, but a form of concussion, termed persistent concussion syndrome (PCS), has symptoms that can persist for months after the event (McCrory et al., 2016).

Researchers have described the mechanism for head injuries using three main theories. The first proposed mechanism for head injury is explained by skull deformation causing brain contusion where the injury severity is based upon the amount of strain to the underlying brain tissues and damaged local blood vessels (Gurdjian and Gurdjian, 1975). A second mechanism can be explained by a change in intracranial pressure due to skull deformation upon impact, causing pressure gradients across the cerebrum and brainstem linked to brain stresses responsible

for concussive traumas (Gurdjian et al., 1966). A third mechanism explains brain injury as a rotational event resulting in relative brain and skull movement and the shearing of the delicate axons that disrupt neural function and therefore cause injury (Holbourn, 1943). While these injury mechanisms have been demonstrated for severe forms of injury, such as intracerebral hematomas and brain contusions, uncommon injuries in women's hockey, they provide valuable insight into an understanding of head injuries with non-visible damage to brain tissue, such as concussion.

2.1.1 Physiology of Concussion

A challenge with sports-related concussions is that injury diagnoses are dependent on symptomology (Delaney et al., 2014). Injured athletes presenting with somatic, cognitive, and emotional symptoms are a result of the physiological changes in the brain that occur after a head impact event causes impulsive loading to the brain (McCrory et al., 2016).

Cerebral pathophysiology is altered following a concussion event beginning with a rapid release of neurotransmitters (Giza and Hovda, 2014). When bound with receptors, a neuronal depolarization occurs causing an influx of calcium (Ca^+) and an efflux of potassium (K^+). The sodium-potassium (Na^+/K^+) pump must operate quickly and repetitively in an attempt to restore membrane potential. This is an energy costly process that can deplete intracellular energy stores (Giza and Hovda, 2014). This period of hyperglycolysis necessary for restorative purposes results in metabolic impairment of processes required for regular functioning. This

can last from 7-10 days, which is commonly listed as the advised recovery period of concussion (McCroory, et al., 2016).

2.1.2 Concussion in Women

According to the American Medical Society for Sports Medicine position statement on concussion in sport (2012), women sustain more concussions than men in sports with similar rules (Covassin, et al., 2003; Agel et al., 2007; Dick et al., 2009).

Further, female athletes report a higher quantity and severity of symptoms in addition to longer post-concussion recovery than male athletes (McLeod and Leach, 2012; Broshek et al., 2005; Kutcher and Eckner, 2010; Covassin et al., 2006). Recent research has proposed a number of explanations describing why women have a higher incidence of concussion. Tierney et al (2005) attributed the differences in concussion incidence to the kinematic and neuromuscular control of the head/neck segment between genders. Females had significantly higher angular accelerations of the head in a combination with lower isometric contraction of the neck muscles during forced flexion and forced extension. They proposed that lower head-neck mass in females resulted in higher rotational accelerations associated with concussion risk. While the participants included in this study were not athletes and the isometric strength values may not be representative of an at risk athletic population, a relationship between anatomical and geometrical characteristics was found to associate with biomechanical injury response. It is also important to note that applied forces in this experiment were too low to be representative of a concussive causing force and therefore cannot directly link the neck strength to female concussion risk. A subsequent study by the same authors (2008) found

significant differences in linear head acceleration, effective head mass, and neck strength between genders when athletes performed a soccer header. While the head response of performing soccer headers did not result in accelerations representative of concussion they do demonstrate gender specific differences when performing sport-specific maneuvers.

Another group of researchers have explored hormone differences as a potential explanation of differences in TBI severity between genders (Emerson et al., 2001; Stein and Hoffman, 2003). Rat brain injury models were administered doses of estrogen prior to a fluid percussive injury, a common protocol for studying brain injury in live subjects, and noted a “protective” quality in comparison with controls (Bramlett and Dietrich, 2001). Although these findings show some promise, the relationship between traumatic brain injury and hormone levels is still unclear and further research is necessary. The higher incidence of concussion for females may also be due to the fact that women are more likely to report their symptoms than men, therefore present a higher risk of injury based on gender differences alone (Gioia et al., 2008; Agel et al., 2011).

2.2 Head Impact Events

Researchers have identified concussive events in ice hockey in an attempt to explain gender differences (Agel et al., 2007; Delaney et al., 2014). The most common event causing concussion in women’s hockey occurs when players fall, hitting their head against the ice or onto the sideboards of the arena. As seen in table 1, fall events cause approximately 50-60% of concussions; however only encompass 30% of all head impacts during in the game (Agel et al., 2007; Delaney et al., 2014; Wilcox et al.,

2014). Despite body checking penalties in women’s hockey designed to limit player contact, collisions cause 27-42% of concussions in elite women’s hockey (Agel et al., 2007; Delaney et al., 2014). This indicates that while fall events occur less frequently than collisions in women’s hockey (Wilcox et al., 2014), they are more likely to cause concussion (Agel et al 2007; Delaney et al., 2014). The frequency and incidences of these types of impacts supports the current research efforts, which look at the biomechanics of women’s ice hockey concussions.

Table 1: Published data of head impact/injury events in elite women's hockey

	Researchers	Head Impact Event	Percentage of Impacts
Concussion	Agel et al., 2007	Falls (to ice, boards)	51%
		Collision (with another player)	42%
		Other (goal, stick, puck)	7%
	Delaney et al., 2014 (n=26)	Falls (to ice, boards)	61%
		Collision (shoulder, elbow, head)	27%
		Other (goal, stick, puck)	12%
Non concussion	Wilcox et al., 2014 (n=242)	Falls (to ice, boards)	29%
		Collision (with another player)	50%
		Other (goal, stick, puck)	21%

The differences between collision and fall events in ice hockey can be described by the surfaces with which a player’s head can contact. Fall events in hockey include the mass of a players head falling onto rigid, immovable surfaces such and ice and side boards where nearly all of the energy in the event is transferred to the head of the player (Hoshizaki et al., 2013). Since all players are required to wear helmets, the severity of a concussion from a fall is a result of the compliance of the surface (ice or boards) and the helmet, the mass of the players head, the velocity of the

event and the impact location (through the center of gravity or not through the center of gravity) (Hoshizaki et al., 2013, 2014; Oeur and Post, 2011). Hockey collisions differ because they involve a player's head colliding with a yielding surface, such as a shoulder or elbow pad, where the amount of energy transferred to the head is largely dependent on the characteristics of the compliance of the body part and helmet, striking mass, and velocity of the player (Hoshizaki et al., 2013, 2014; Rousseau & Hoshizaki 2015). Both events can result in concussion in women's hockey but each event creates unique dynamic response characteristics (Hoshizaki et al., 2013; 2014). Reconstructions of falls and collisions have revealed significantly different acceleration-time curve shapes where a fall can be described as a high magnitude, low duration event and a collision can be described as low to mid magnitude, and relatively long duration event (Doorly and Gilchrist, 2006; Kendall et al., 2012).

2.3 Impact Conditions

Head impact events are typically described by the magnitude of the impact characteristics known to contribute to the risk and severity of head injury (Hoshizaki et al., 2014). Researchers have determined that impact characteristics such as compliance, mass, velocity and location/direction influence the dynamic response of the head and brain tissue response (Zhang et al., 2001a; Pellman et al., 2003; Kleiven, 2003; Post et al., 2012a). It is important to understand how varying levels of these impact characteristics contribute to dynamic response and brain tissue deformation and the corresponding risk of head injury in elite women's hockey.

2.3.1 Location

The impact location on the head has been reported as influential to head injury incidence and severity (Gurdjian et al., 1953; Gennerelli et al., 1982; Hodgson et al., 1983). In primate research it was reported that angular accelerations of the head in the lateral direction (yaw- direction) were a better predictor of concussion when compared to angular accelerations in the anterior-posterior direction (Gennarelli et al., 1982). Primate models were also used by Hodgson et al. (1983) to find that impacts to the side of the head created higher linear and angular accelerations than impacts to other locations (Hodgson et al., 1983).

The most frequent head impact locations that have been reported to cause concussions in women's hockey are the side and back of the head (Delaney et al., 2014). However, this report does not consider that these typical locations could be specific to event type, which could also be important when evaluating the full picture of the event that leads to injury.

In hockey, head impacts can occur to the same area of the head but can come from various directions. It has been found that impacts through the center of gravity of the head (centric) result in higher linear acceleration compared to angular accelerations. Further, impacts that are not through the center of gravity (non centric) of the head result in higher angular acceleration (Post et al., 2011; 2013). In this comparison of centric and non centric impacts, it was also found that peak angular accelerations were more highly correlated with the brain deformation metric, maximum principal strain (MPS) which indicates a relationship between non centric impacts and MPS (Post et al., 2013).

2.3.2 Velocity

Increasing velocity has been shown to increase post-impact head dynamic response in sport reconstruction research representing collisions and falls (Rousseau et al., 2009a; Rousseau et al., 2009b; Post et al., 2013a Post et al., 2012a; Kendall et al., 2012b; Rousseau et al., 2014). As a result, it is important to consider the effect of velocity on head impact events in elite women's hockey.

Elite women's hockey players can reach a velocity of 8.1 m/s (30 km/h) on a high velocity performance test (Bracko et al., 2001). However, players travel at various speeds throughout a game and most in-game play requires players to stop and start in small zones of the ice with insufficient space to reach top speed. As a result, collisions between players at full speed rarely occur. The velocity of elite women's hockey players colliding with each other has not been reported in the literature, collisions between NHL men's hockey players that have caused concussion range from 4.1-9.0 m/s, averaging 6.0 m/s (Rousseau thesis, 2014). Elite men's hockey players have been reported to skate up to velocities of 13 m/s (47km/h) (Stuart & Smith, 1995).

2.4 Measures of Concussion

When a direct head impact occurs, the forces from the impact manifest as local pressure changes and shear strain to tissue as the brain moves inside the skull (Holbourn, 1943). As the force of the head impact increases, these changes in the brain tissue can pass the tolerance level necessary for normal brain function

(Horgan, 2005). When this level of tolerance is exceeded, physiological events result in the functional disruptions reported as symptoms of concussion (Giza and Hovda, 2001). Researchers have measured the forces applied to the head during an impact as a way to understand the levels required to cause concussion versus more serious forms of traumatic brain injury. Since pressure changes and brain tissue strain cannot be measured in vivo, post-impact linear and angular acceleration of the head have been used as measurable result of the energy transfer seen in head impacts (Holbourn, 1943). Since concussion is a physiological disruption caused by damage to brain tissue, researchers have designed finite element (FE) models of the brain and its structures. These models represent the strain to brain tissue in head impact scenarios. As a result, brain tissue deformation values generated from FE models are used in concussion biomechanics research.

2.4.1 Angular Acceleration

A link has been made between post-impact rotational acceleration of the head and resulting strain to brain tissue (Gennarelli et al., 1971; Gennarelli, et al., 1972; Gennarelli, et al., 1979; Adams et al., 1981). Holbourn (1943) originally championed this concept by demonstrating how water within a flask moves. As the flask accelerates or decelerates, water around the outside of the flask moves more quickly than the water in the middle of the flask. The difference in motion causes the water molecules to separate. Holbourn (1943) proposed that the same phenomena could be applied to brain tissue inside the skull. The relative motion between brain tissues as they accelerate causes stretching or shear of the tissue that is responsible for the functional disruptions seen in minor traumatic head injury.

Further investigation into the role of rotational accelerations on brain injury was done using monkeys (Gennarelli 1971; 1972). It was demonstrated that by adjusting rotational acceleration in magnitude and duration the resulting injuries could be as severe as diffuse axonal injury and subdural hematoma. It was further found that when impacts resulting in mainly rotational accelerations were applied to monkey models, concussive injury occurred more frequently than impacts resulting in mainly linear translation of the head (Gennarelli et al., 1972).

Although rotational acceleration is an important component when describing concussive injury mechanism, in the context of sport concussion, an impact will always include both a rotational and linear component. As a result, research into the biomechanics of sport concussion describes dynamic response using both linear and rotational acceleration (Post and Hoshizaki, 2012).

2.4.2 Linear Acceleration

Linear acceleration has been used as an important measure in head injury research. Early work in this area proposed head injuries caused by a pressure gradient within the skull at impact (Gurdjian and Lissner, 1961). Using animal models, this research was able to correlate injurious pressure gradients at impact with linear acceleration of the head post-impact (Gurdjian et al., 1966). Further, in a comparison of injuries caused by direct impact to the head and injuries involving non-impact, or whiplash mechanisms, it was shown that while concussion can occur in non-impact scenarios, the accelerations needed were much higher than direct impact scenarios (Ommaya et al., 1966; 1971). Later it was acknowledged that head injury is more likely caused

by a combination of pressure gradient from focal injury and damaging brain tissue strain caused by relative brain/skull motion (Gurdjian and Gurdjian, 1975).

Since head injuries in sport are primarily suffered as a result of direct impacts to the head, current helmet safety standards use peak linear acceleration as pass/fail criteria (Canadian Standards Association, 2009, Snell Memorial Foundation, 2010; American Society for Testing and Materials, 2014). As a result, it is important to investigate peak linear acceleration in head impact testing research.

2.4.3 Maximum Principal Strain

Linear and angular accelerations have been used together to describe head injury severity. However, these variables are only the measurable description of head motion that can cause damage to brain tissue (Holbourn, 1943). Since measures of brain tissue deformation in vivo are not plausible, finite element models have been developed based on material characteristics of brain structures to approximate brain tissue response metrics (Bain and Meaney, 2000; Kleiven 2007; Zhang et al, 2003; King et al., 2003; Horgan and Gilchrist, 2004). An important brain tissue deformation measure is maximum principal strain (MPS), which represents the tensile strain (stretching) of a section of tissue along its principal axis (Bain and Meaney, 2001). MPS is presented as a percentage of strain past the tissue's original length and is representative of the brain tissue damage caused by an injurious head impact (Bain and Meaney, 2001; Silva, 2006).

Rotational acceleration correlates higher with maximum principal strain than linear acceleration (Forero Rueda et al, 2010). As a result, rotational acceleration has been proposed as the most influential mechanism on the severity of concussive injury

(Zhang et al., 2004). Brain tissue deformation measures such as MPS are important in understanding how the dynamic response of a head impact event influences the brain tissue resulting in the metabolic cascade of concussion.

2.5 Proposed Injury Thresholds

Concussion injuries occur when an external force causes changes to the blood-brain barrier. Injury may even occur at lower levels of trauma that do not necessarily result in symptoms that are classically described as concussion. This low level trauma can be difficult to detect as it occurs at the cellular level (Giza, 2011). This has prompted researchers to describe the dynamic response and brain tissue response variables at the point of tolerance (Zhang, 2001; Zhang et al, 2004; Kleiven 2007, Willinger and Baumgarthner, 2003). Zhang et al., (2004) used physical models of NFL concussion events to determine the linear and rotational acceleration values associated with 25%, 50% and 80% probability of concussion. It was found that the linear acceleration resulting in a 25% probability of injury was 66g, 50% probability was 82g and 80% probability of injury was 106 g. Further it was found that the rotational acceleration resulting in a 25% probability of injury was 4600 rad/s², 50% probability was 5900 rad/s² and 80% probability of injury was 7900 rad/s². Willinger and Baumgarthner (2003) found concussion probability with a rotational acceleration measure between 3000 and 4000 rad/s². Similarly, with MADYMO reconstructions of concussive events in rugby, McIntosh et al (2014) measured 50% concussion probability to have a linear acceleration of 65 g and a rotational acceleration of 3958 rad/s².

Similar research was conducted to determine the strain values that represent probability of concussive injury. Zhang et al (2004) found that brain tissue strain of 0.14, 0.19 and 0.24 are representative of 25%, 50% and 80% probability of injury. Kleiven and associates (2007) reported brain strain values (MPS) representative of 50% concussion risk to measure 0.21 in the corpus callosum and 0.26 in the grey matter. Concussion risk probabilities are valued pieces of research because it allows reconstruction of sport concussion results to be interpreted in light of the real world implications of impacting scenarios.

3 CHAPTER 3: METHODOLOGY

3.1 Head Impact Event Classification

This thesis involves two parts. Part one consists of classifying head impact events in women's hockey. Types of head impact events were identified and analyzed to determine the associated impacting velocities and locations for each event. This was a necessary first step to inform the second part of this research, which included reconstructing the injury events to compare the biomechanical responses associated with each head impact event.

Part one was completed to document distinct head impact events in elite women's hockey, which required locating video of head impacts. Fifteen full game videos from Canadian Women's Hockey League (CWHL) online archives, National Women's Hockey League (NWHL) online archives and televised International Ice Hockey Federation (IIHF) World Hockey Championships were viewed and head impact events were identified for further evaluation. When a head impact event met the event inclusion selection criteria, a copy of the event was saved using WM capture software (San Anselmo, CA).

3.1.1 Event Criteria

Head impact video clips were selected from elite women's hockey games from the CWHL, NWHL or IIHF World Hockey Championships. An event was saved if there was a collision between two players where the head was directly impacted by an opponents' body part, if a player fell to the ice and hit the head against the ice, or if a player's head directly impacted the surrounding boards.

3.1.2 Event Analysis

3.1.2.1 Kinovea

To establish impact velocity, direction, and location, Kinovea 0.8.20 (open source, kinovea.org) was utilized to obtain on-ice head impact parameters. This method required the selected videos to meet several inclusion criteria. These criteria included (1) head impact event must be a single impact to the head, (2) player's head must be the initial point of contact, (3) the dimensions of the ice rink must be known, (4) sufficient number of lines and circles on the ice must be visible in the camera's view and (5) the head impact event must have been fully visible to the camera based on the angle that it was filmed. If these criteria were not met, the event was excluded from the study.

To determine impact velocity using Kinovea video analysis, the distance between impact surface (shoulder, boards...etc) and the athlete's head was superimposed to the ice and measured 5 frames before the impact occurred. Velocity was calculated using this distance and the captured frame rate of 25 frames/sec. If two moving players were involved in a collision, relative velocity was calculated using the same method. The lines and circles on the ice were used to create a perspective grid, which served as a reference scale to convert pixels to metres. Impact location was determined by a close up view of the collision. Impact location was described on the impact location grid shown in figure 1.

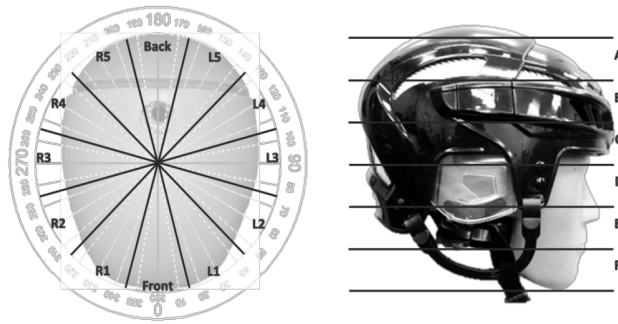


Figure 1: Head impact location grid (Rousseau thesis, 2014)

3.1.2.2 *Mathematical Dynamic Model (MADYMO)*

In the four head to ice events where the motion before impact was in the vertical direction, velocity estimates were gathered using a MADYMO model (TASS International, The Netherlands) where the limbs and positioning of the model were manipulated to follow the body motion in the video. The body position of the player was recreated to match the frame of video as the player began to fall, as the player hit the ice and position after the impact.

3.1.3 *Results*

A total of 44 head impact events met the inclusion criteria and were saved using WM Capture 7 software (San Anselmo, CA). 35 of these events could be categorized into a head to boards, shoulder to head or a head to ice impact event. 9 were not further analyzed because they either the head impact event could not be determined or was a head impact event not being investigated in this study (ie. punch, elbow) Head impact events were gathered from approximately 15 hours of game play or 15 games (Table 2). This 15 game sample represents the number of games that were





archived online so it does not represent a full season, but rather what was available to the public to view.

Table 2: The distribution of the 44 head impact event videos collected from 15 hours of game play.

Head Impact Event	Number of videos collected
Shoulder-to-head	13
Head-to-boards	18
Head-to-ice	4

Each of the shoulder-to-head, head-to-boards and head-to-ice event videos were analyzed for location of impact and compared to the location grid depicted in Figure 1. The three most frequent locations for each event were recorded and were then used as high, medium and low frequency locations in the head impact testing research design (Part 2). Tables 3, 4 and 5 outline the locations seen in each event.







Table 3: The three most frequent locations for 18 head-to-boards impact events in elite women's hockey

Frequency	View 1	View 2
High: R3B <i>n=7</i>		
Medium: R1/2C <i>n=6</i>		

Low: Back C
n=1









Table 4: The three locations for 4 head-to-ice impact events in elite women's hockey

Frequency	View 1	View 2
High: Back C <i>n=2</i>		
Medium: R1/2C <i>n=2</i>		
Low: R3C <i>n=0</i>		

In the case of head to ice impact high, medium and low frequency could not be determined by the locations found in the 15 games watched. R3C was considered to be the low frequency event because it is a side impact, which has been reported to be a common concussion location in women's hockey (Delaney et al., 2014). Back C was theorized to be high frequency because if a player does fall backwards, they would not be able to use their arms to stop themselves like they would if they fell forward.

Table 5: The three most frequent locations for 13 shoulder-to-head impact events in elite women's hockey

	View 1	View 2
High: R1/2D Non centric <i>n</i> =7		
Medium: R1/2D Centric <i>n</i> =3		
Low: R3D <i>n</i> =2		

Head impact event videos that met the event analysis criteria were analysed for velocity of impact. Ten shoulder-to-head event videos and six head-to-boards events were analyzed and velocities obtained using Kinovea 0.8.20 (open source, kinovea.org) software, while four head-to-ice events were analyzed for velocity using MADYMO modeling software. Table 6 presents head impact event velocity data. In a study that investigated the accuracy of calculating speed using video analysis software it was found that the speed error associated with this method of video analysis ranged between 0.7-1.3 m/s for low speed and high speed impacts (Post et al., 2018). Based on this, the range of velocities tested (average -1 m/s, average, average +1 m/s) cover the range of potential velocity calculation error.

Table 6: Velocity of head impact events in elite women's hockey

Head Impact Event	<i>N</i>	Range (m/s)	Mean (m/s)
Shoulder-to-Head	10	2.9-7.3	4.6 (1.2)
Head-to-Boards	6	2-3.7	3.2 (0.6)
Head-to-Ice	4	3-6.5	4.8 (1.4)

3.2 Head Impact Testing Protocol

Based on the classification of head impact events in women's hockey and the impacting conditions that describe each event, a head impact testing protocol was developed. The goal of this research protocol was to understand the dynamic response and brain tissue deformation values of head impact events in elite women's hockey.

The three most frequent head impact events in women's hockey include shoulder-to-head, head-to-boards, and head-to-ice (Table 2). Each of these events was tested at three velocities and at three locations. The testing velocities were established as the average velocity for each event analyzed in part one with the lower and upper range velocities ± 1 m/s from the average. The three locations for each event were determined to be the three highest frequency locations.

3.2.1 Equipment

3.2.1.1 Linear Impactor

A pneumatic linear impactor was used to represent shoulder-to-head impact conditions in elite women's hockey. The system consists of a pneumatically accelerated impacting arm encased in a standing frame (length 1.28 ± 0.01 m; mass

13.1 ± 0.1 kg). When engaged the arm moves towards a helmeted headform mounted on a sliding table allowing it to slide backward with little resistance after impact. This sliding table that supports the Hybrid III headform can be adjusted to five degrees of freedom including fore-aft (x-axis), lateral (y-axis), up-down (z-axis), fore-aft (y-axis), and axial (x-axis) rotation of the neckform. This allowed the impact location and direction described from the video analysis to be accurately reflected by the headform test set up (Walsh et al., 2011). An electronic time gate measures impact velocity just prior to impact and was used to match the impact velocities obtained from video analysis.

A shoulder-to-head event is considered a high mass event where the striking mass of the player has been calculated to be approximately 15% of the striking players mass, which is 14 kg (Rousseau & Hoshizaki, 2015). Further, Karton demonstrated that the effect of striking mass had little effect above 10 kg when using an MEP striker (Karton et al., 2013). The average body mass of a women's hockey player on the Canadian national women's hockey team is listed as 70kg (hockeycanada.ca). Based on this information, effective mass can be calculated as approximately 10.5 kg. In this study, a striking mass of 13.1 kg was used.

A shoulder pad cap consisting of a nylon disc covered with 142mm of vinyl nitrate R338V foam material under a Reebok 11K shoulder pad was mounted on the end of the impacting arm to represent shoulder-to-head collisions. Rousseau et al., 2009, conducted the development of this striking surface by matching the linear acceleration duration and magnitudes of shoulder-to-head collisions in ice hockey using volunteer male skaters (Rousseau et al., 2009).

3.2.1.2 Monorail Drop Rig

The monorail drop rig consists of a Hybrid III headform attached to a neckform is released from a height along a 4.7 m rail and onto an anvil. A pneumatic piston is responsible for releasing the drop carriage and attached headform where impact velocity was captured using a time gate located 2 mm above the impact. The impact anvil can be adjusted to represent various surfaces including ice or hockey boards. In this study, the monorail drop rig was used to represent head to ice falls and head to boards impacts.

3.2.1.3 Hybrid III Headform

In this study, a Hybrid III 5th-percentile female headform with a circumference of 21.2 inches and comprised of steel covered in a vinyl skin, was used to recreate head impact events in women's hockey (Humanetics, Plymouth, MI, USA). The headform was attached to the impacting arm and drop rig via an unbiased female neckform. This unbiased neckform was scaled from the 50th-Hybrid III neckform with four centred and unarticulated rubber butyl disks (radius 27.5 mm; height 18.0 mm) recessed slightly (3.2 mm) and serially inside aluminum disks (radius 34.5 mm; height 12.5 mm) (Figure 2).



Figure 2: Unbiased neckform from rear, front and left side view

Nine single-axis accelerometers positioned in a 3-2-2-2 array measured the acceleration in the x (forward/backward), y (left/right) and z (up/down) direction when triggered at 3 g by an impact. DTS TDAS control system was used for processing accelerometer data (20,000 htz) to obtain linear and rotational acceleration values.

3.2.2 Finite Element Model

The University College Dublin Brain Trauma Model (UCDBTM) developed by Horgan and Gilchrist (2003; 2004) was used to determine maximum principal strain (MPS) of brain tissue for head impact events in elite women's hockey.

Horgan and Gilchrist (2003) modeled the shear behaviour of brain tissue as viscoelastic and the compressive behaviours of brain tissue as elastic. The model was developed using CT and MRI scans and validated using cadaver data (Horgan and Gilchrist, 2003). Linear and angular acceleration time histories were used as an input to the model to calculate brain tissue deformation. Results are presented as a gradient of deformation from low to high. In terms of maximum principal strain, results are presented as a percentage of strain. This model has been used to describe brain tissue deformation in many head impact scenarios (Rousseau thesis, 2014; Post et al., 2013, 2014, 2014a; Post and Kendall, 2015).

3.3 Research Design

The test design consisted of three head impact events at three velocities and three locations for a total of 27 impact set-ups (3x3x3). The three velocities were chosen to be the average calculated velocity of each impact event, an upper range of +1 m/s from the average and a low range of -1 m/s from the average. The three locations were chosen to be a high frequency location which represents the location that was found to be impacted the most often, a medium frequency location, which represents the location that was found to be impacted the second most often, and a low frequency location which represents the location that was found to be impacted the third most often. With three trials of each impacting set-up there was a total of 81 impacts. The impact set-ups are outlined in tables 9, 10 and 11

Table 9: Fully crossed research design for the **shoulder-to-head** event of a 5th percentile Hybrid III Headform

	A1	A2	A3
B1	A1B1	A2B1	A3B1
B2	A1B2	A2B2	A3B2
B3	A1B3	A2B3	A3B3

A1 = R1/2 D (non-centric) B1 = 3.6 m/s
 A2 = R1/2 D (centric) B2 = 4.6 m/s
 A3 = R3/D B3 = 5.6 m/s

Table 10: Fully crossed research design for the **head-to-boards** event of a 5th percentile Hybrid III Headform

	C1	C2	C3
D1	C1D1	C2D1	C3D1
D2	C1D2	C2D2	C3D2
D3	C1D3	C2D3	C3D3

C1 = R3 B D1 = 2.2 m/s
 C2 = R1/2 C D2 = 3.2 m/s
 C3 = Back C D3 = 4.2 m/s

Table 11: Fully crossed research design for the **head-to-ice** event of a 5th percentile Hybrid III Headform

	E1	E2	E3
F1	E1F1	E2F1	E3F1
F2	E1F2	E2F2	E3F2
F3	E1F3	E2F3	E3F3

E1 = Back C F1 = 3.8 m/s
 E2 = R1/2 C F2 = 4.8 m/s
 E3 = R3 C F3 = 5.8 m/s

3.4 Statistical Analysis

To determine the influence of head impact event, location and velocity on dynamic response and brain tissue deformation, a three-way Multivariate Analysis of Variance (MANOVA) was conducted with the three independent variables of head impact event, location and velocity and the dependent variables of peak resultant linear acceleration, peak resultant angular acceleration and maximum principal strain to determine relationships between dependent variables.

A three-way ANOVA will determine main effects for event, location and velocity and tukey's post hoc tests were then conducted to determine mean comparisons between variables. Significance was accepted at $p < 0.05$.

4 CHAPTER 4: RESULTS

The overall objective of this study was to describe the three distinct head impact events that commonly result in concussion injury in elite women's hockey (head to boards, head to ice, and shoulder to head) using peak resultant linear acceleration, the peak resultant angular acceleration and the maximum principal strain. A secondary objective was to examine the effect of variable impact locations and incremental increases in velocity on peak resultant dynamic response and maximum principal strain values.

4.1 Multivariate Analysis of Variance (MANOVA)

The three-way MANOVA yielded a significant main effect for independent variables head impact location (Wilks' $\lambda < 0.01$, $F = 215.3$) and velocity (Wilks' $\lambda < 0.01$, $F = 46.3$) when considering peak resultant linear acceleration, peak resultant angular acceleration and maximum principal strain. Head impact event did not yield a significant main effect (Wilks' $\lambda = 1.0$) indicating that the variance cannot be described by head impact event itself, which suggests a relationship between dependent variables.

4.1.1 ANOVA Head Impact Event

4.1.1.1 Peak Resultant Linear Acceleration

When considering peak resultant linear acceleration, a significant difference was found between head impact events ($p < 0.01$) with the head to ice events yielding the highest mean ($M_I = 123.6 \text{ g} \pm 47.6 \text{ g}$) followed by the head to boards event ($M_B = 34.1$

$g \pm 10.8 g$) and the shoulder to head event ($M_s = 18.6 g \pm 4.7 g$). As a result, the null hypothesis, no effect between head impact event and peak linear acceleration was rejected. Tukey's post hoc mean comparison tests revealed that peak resultant linear acceleration was significantly different between head to ice and both head to boards ($p < 0.01$) and shoulder to head ($p < 0.01$). However, head to boards was not significantly different from shoulder to head ($p = 0.1$). Figure 3 depicts the peak resultant linear accelerations of head to boards, head to ice and shoulder to head impact events at average velocity as well as the frequency each event occurred at in this study.

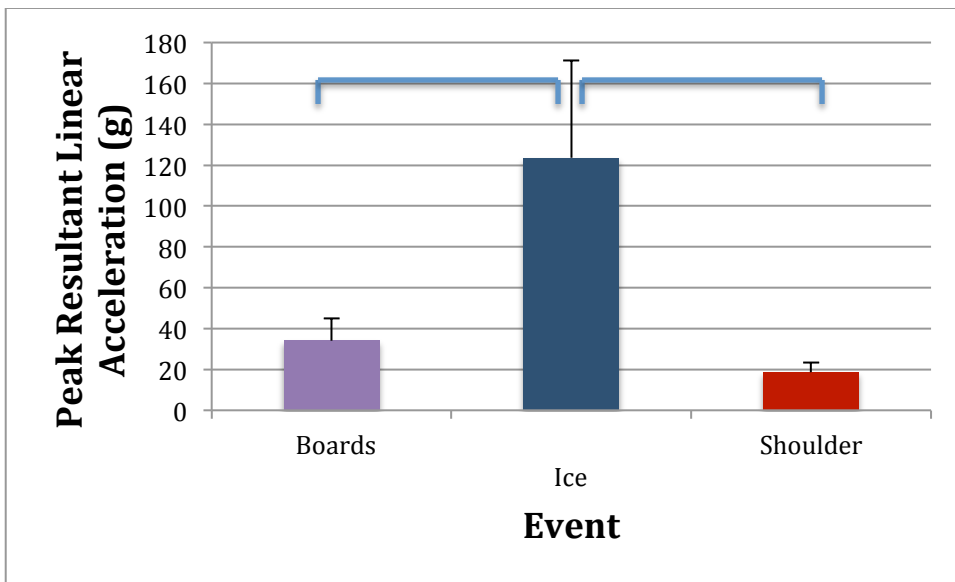


Figure 3: The average peak resultant linear acceleration of the three head impact events, head to boards, head to ice, and shoulder to head. Blue square brackets indicate significant differences.

4.1.1.2 Peak Resultant Angular Acceleration

In terms of peak resultant angular acceleration, a significant difference was found between head impact events ($p < 0.01$) with the head to ice events yielding the highest mean ($M_I = 9518.2 \text{ rad/sec}^2 \pm 4501 \text{ rad/sec}^2$) followed by the shoulder to

head event ($M_S = 3341.3 \text{ rad/sec}^2 \pm 855 \text{ rad/sec}^2$) and the head to boards event ($M_B = 2386.2 \text{ rad/sec}^2 \pm 900 \text{ rad/sec}^2$). As a result, the null hypothesis stating no effect between head impact event and peak angular acceleration was rejected. Tukey's post hoc tests showed that peak resultant angular acceleration was significantly different between head to ice and both shoulder to head ($p < 0.01$) and head to boards ($p < 0.01$). However, shoulder to head was not significantly different from head to boards ($p = 0.376$). Peak resultant angular accelerations of head to boards, head to ice and shoulder to head impact events at average velocity as well as the frequency each event occurred at in this study are shown in figure 4.

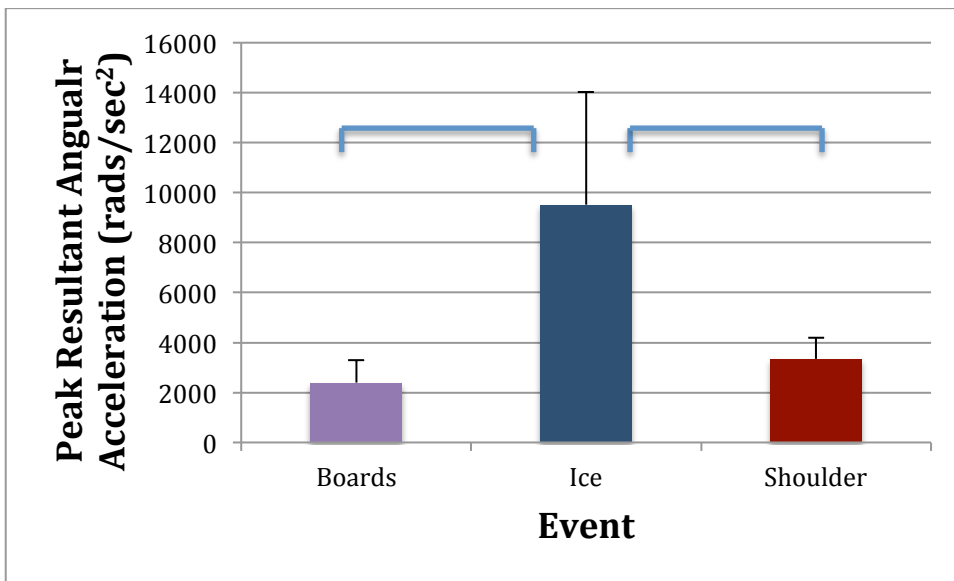


Figure 4: The average peak resultant angular acceleration of the three head impact events, head to boards, head to ice, and shoulder to head. Blue square brackets indicate significant differences.

4.1.1.3 Maximum Principal Strain

There was also a significant difference found between events in terms of maximum principal strain ($p < 0.01$) with the head to ice events yielding the highest mean ($M_I = 0.51 \pm 0.13$) followed by the shoulder to head event ($M_S = 0.27 \pm 0.08$) and the head

to boards event ($M_B = 0.19 \pm 0.06$). As a result, the null hypothesis, no effect between head impact event and maximum principal strain was rejected. Tukey's post hoc tests determined that MPS values were found to be significantly different between head to ice and shoulder to head ($p < 0.01$), head to ice and head to boards ($p < 0.01$), and between shoulder to head and head to boards ($p < 0.01$). Figure 5 shows maximum principal strain of the three head impact events at average velocity as well as the frequency each event occurred at in this study.

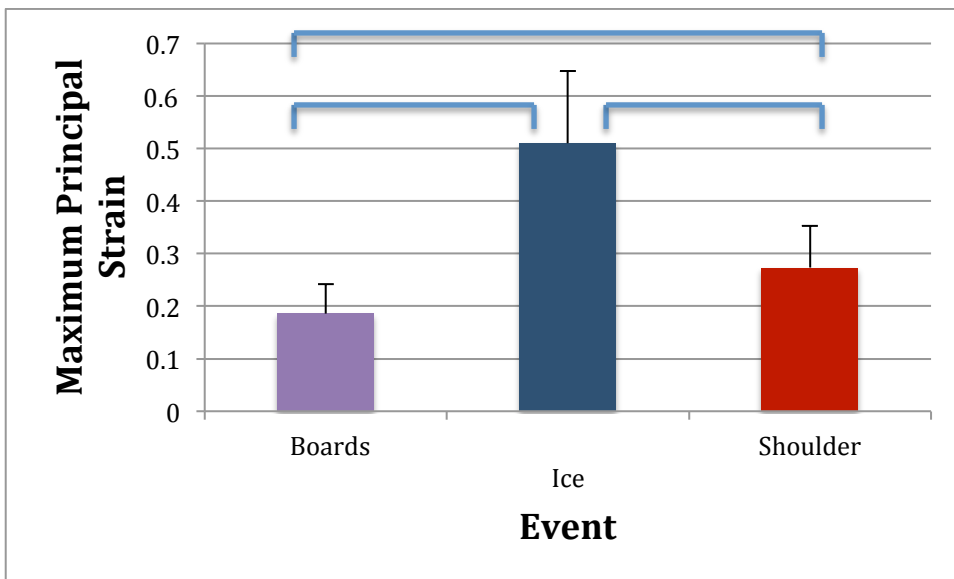


Figure 5: The maximum principal strain of the three head impact events, head to boards, head to ice, and shoulder to head. Blue square brackets indicate significant differences.

4.1.2 ANOVA Velocity

The velocities compared in this section represent the average velocities calculated from the events used in this study. These velocities do not represent the highest possible velocities the event could occur at in women's hockey, rather the velocity the event is most likely to occur at based on the velocity of events analyzed.

4.1.2.1 Peak Resultant Linear Acceleration

The results show that as impact velocity of an event increases, there is also an increase in peak resultant linear acceleration (Figure 6). Falls to the ice resulted in the highest peak resultant linear acceleration ($Vel_{avg} = 4.8 \text{ m/s}$; $M = 121g \pm 51 \text{ g}$), followed by head to board falls ($Vel_{avg} = 3.2 \text{ m/s}$; $M = 31.1 \text{ g} \pm 4.2 \text{ g}$), and shoulder to head collisions ($Vel_{avg} = 4.6 \text{ m/s}$; $M = 19.3 \text{ g} \pm 2.9 \text{ g}$).

Statistically, a significant main effect was found for velocity on peak resultant linear acceleration ($p < 0.01$). Tukey's post hoc test revealed significant differences for peak resultant linear acceleration between all head to ice and head to boards velocities. For shoulder to head collisions the high velocity shoulder to head impact ($Vel = 5.6 \text{ m/s}$; $M = 22.7 \text{ g} \pm 3.2 \text{ g}$) was not significantly higher compared to the average velocity ($Vel = 4.6 \text{ m/s}$; $M = 19.3 \text{ g} \pm 2.9 \text{ g}$; $p = 0.11$). Also, the high velocity shoulder to head impact ($Vel = 5.6 \text{ m/s}$; $M = 22.7 \text{ g} \pm 3.2 \text{ g}$) did not result in a significantly different response compared to the low velocity head to boards impacts ($Vel = 2.2 \text{ m/s}$; $M = 23.8 \text{ g} \pm 1.8 \text{ g}$; $p = 0.99$).

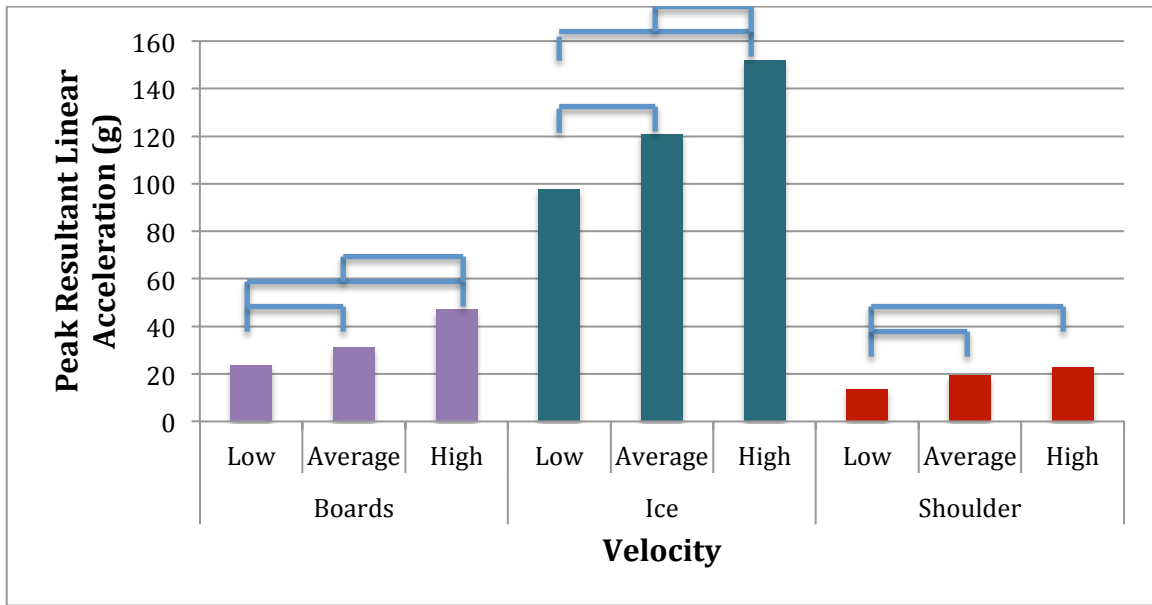


Figure 6: The influence of velocity on peak resultant linear acceleration for head to boards, head to ice, and shoulder to head impact events. Blue square brackets indicate significant relationships.

4.1.2.2 Peak Resultant Angular Acceleration

Similarly, as impact velocity of an event increases, there is also an increase in peak resultant angular acceleration (Figure 7). Falls to the ice resulted in the highest peak resultant angular acceleration ($Vel_{avg} = 4.8 \text{ m/s}$; $M = 9222 \text{ rad/s}^2 \pm 4297 \text{ rad/s}^2$), followed by shoulder to head collisions ($Vel_{avg} = 4.6 \text{ m/s}$; $M = 3556 \text{ rad/s}^2 \pm 197.4 \text{ rad/s}^2$), and head to boards impacts ($Vel_{avg} = 3.2 \text{ m/s}$; $M = 2168 \text{ rad/s}^2 \pm 37.3 \text{ rad/s}^2$).

Statistically, a significant main effect was found for velocity on peak resultant angular acceleration ($p < 0.01$). Tukey's post hoc test revealed that head to ice fall velocities were all significantly different from each other ($p < 0.05$) and all head to boards impact velocities were significantly different from each other ($p < 0.05$). For shoulder to head collisions, the low velocity impact ($Vel = 3.6 \text{ m/s}$; $M = 2298$

rad/s² ± 118.4 rad/s²) was significantly lower than both the average velocity impact (Vel= 4.6 m/s; M= 3556 rad/s² ± 197.4 rad/s²; *p*<0.05) and the high velocity impact (Vel= 5.6 m/s; M= 4170 rad/s² ± 372.8 rad/s²; *p*<0.05) however, the average velocity impact was not significantly lower than the high velocity impact (*p*= 0.062). Further, the low velocity shoulder to head collision impact (Vel= 3.6 m/s; M= 2298 rad/s² ± 118.4 rad/s²) did not result in a significantly higher response compared to the average velocity head to boards impact (Vel= 3.2 m/s; M= 2168 rad/s² ± 37.3 rad/s²; *p*= 0.99) and the average velocity shoulder to head collision impact (Vel= 4.6 m/s; M= 3556 rad/s² ± 197.4 rad/s²) did not result in a significantly higher response compared to the high velocity head to boards impact (Vel= 4.2 m/s; M= 3457 rad/s² ± 526.2 rad/s²; *p*= 0.99).

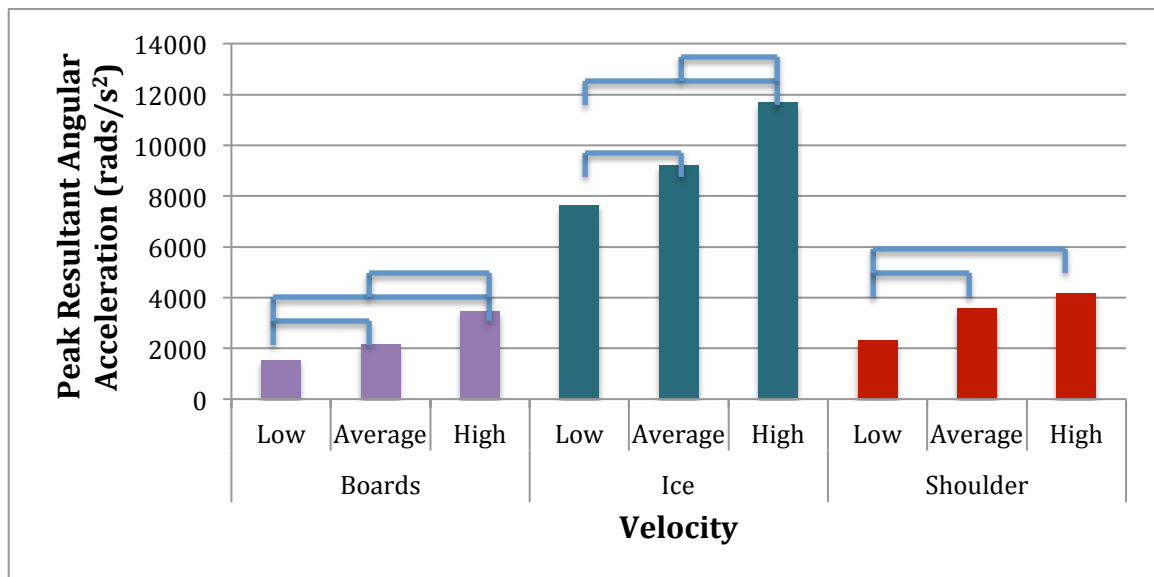


Figure 7: The influence of velocity on peak resultant angular acceleration for head to boards, head to ice and shoulder to head impact events. Blue square brackets indicate significant relationships.

4.1.2.3 Maximum Principal Strain

As impact velocity of an event increases, maximum principal strain also increases (Figure 8). Falls to the ice resulted in the highest maximum principal strain ($Vel_{avg}=4.8$ m/s; $M=0.49\pm0.12$), followed by shoulder to head collisions ($Vel_{avg}=4.6$ m/s; $M=0.29\pm0.04$), and head to boards impacts ($Vel_{avg}=3.2$ m/s; $M=0.18\pm0.04$).

Statistically, a significant main effect was found for velocity on maximum principal strain ($p<0.01$). Tukey's post hoc test revealed significant differences for MPS between all velocities except for between the low velocity shoulder to head collision impact of 3.6 m/s ($M=0.19\pm0.02$; $p=0.99$) and the average velocity head to boards impact of 3.2 m/s ($M=0.18\pm0.04$ $p=0.99$).

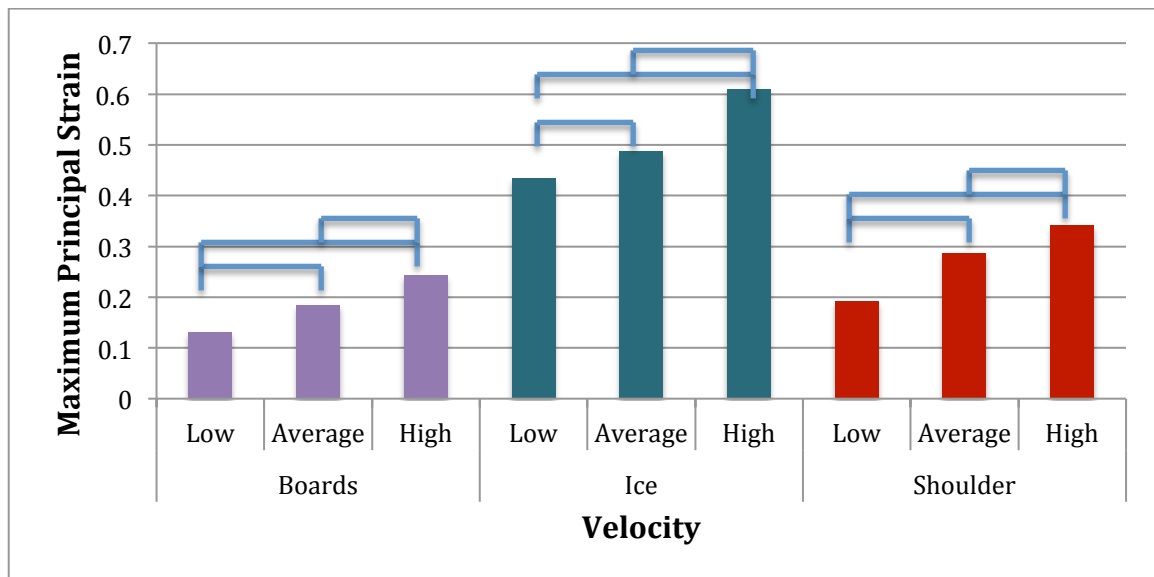


Figure 8: The influence of velocity on maximum principal strain for head to boards, head to ice and shoulder to head impact events. Blue square brackets indicate significant differences.

4.1.3 ANOVA Location

4.1.3.1 Peak Resultant Linear Acceleration

Further, falls into the boards and falls onto the ice result in higher peak resultant linear acceleration when the impact location is to the back of the head (Back C) compared to other locations. Shoulder to head collisions to the side of the head (R3D) result in the highest peak linear acceleration response compared to other locations (Figure 9).

Statistically, a significant main effect was found for location on peak resultant linear acceleration ($p < 0.01$). Tukey's post hoc test showed that significant differences were also found between all head to ice locations ($p < 0.01$). None of the shoulder to head event locations (R12D non centric, R12D centric, or R3D) were significantly different from each other ($p > 0.05$) and only the Back C location of the head to boards event was significantly different from the other two locations (R3B and R12C).

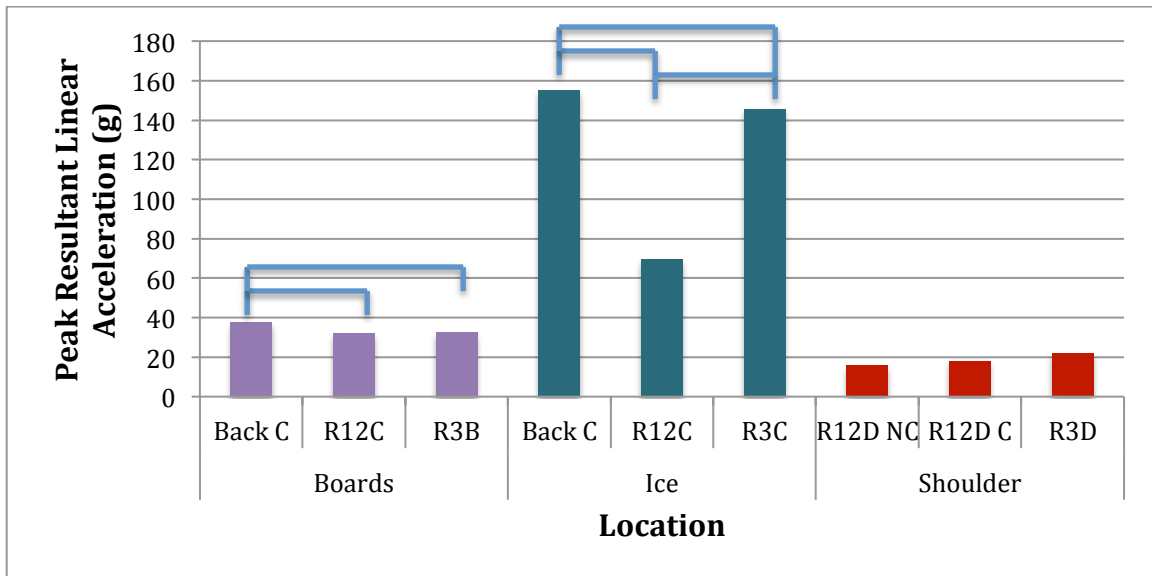


Figure 9: The influence of location on peak resultant linear acceleration for head to boards, head to ice and shoulder to head impact events. Blue square brackets indicate significant differences.

4.2.3.2 Peak Resultant Angular Acceleration

Further, falls into the boards or onto the ice as well as shoulder to head collisions result in higher peak resultant angular acceleration when the impact location is to the side of the head (R3B, R3C, and R3D respectively) when compared to other locations (Figure 10). Falls to the ice to the R3C location resulted in the highest peak resultant angular acceleration ($M= 14623 \text{ rad/s}^2 \pm 2913 \text{ rad/s}^2$), followed by shoulder to head collisions to the R3D location ($M= 3485 \text{ rad/s}^2 \pm 1196 \text{ rad/s}^2$), and head to boards impacts with a R3B impact location ($M= 2913 \text{ rad/s}^2 \pm 1178 \text{ rad/s}^2$). A significant main effect was found for location in terms of peak resultant angular acceleration ($p < 0.01$). Tukey's post hoc test revealed significant differences between all head to ice event locations and all other locations ($p < 0.05$). However, none of the shoulder to head event locations (R12D non centric, R12D centric, or R3D) were significantly different from each other ($p > 0.05$) and none of the head to

boards locations (Back C, R12C, R3B) were significantly different from each other ($p>0.05$).

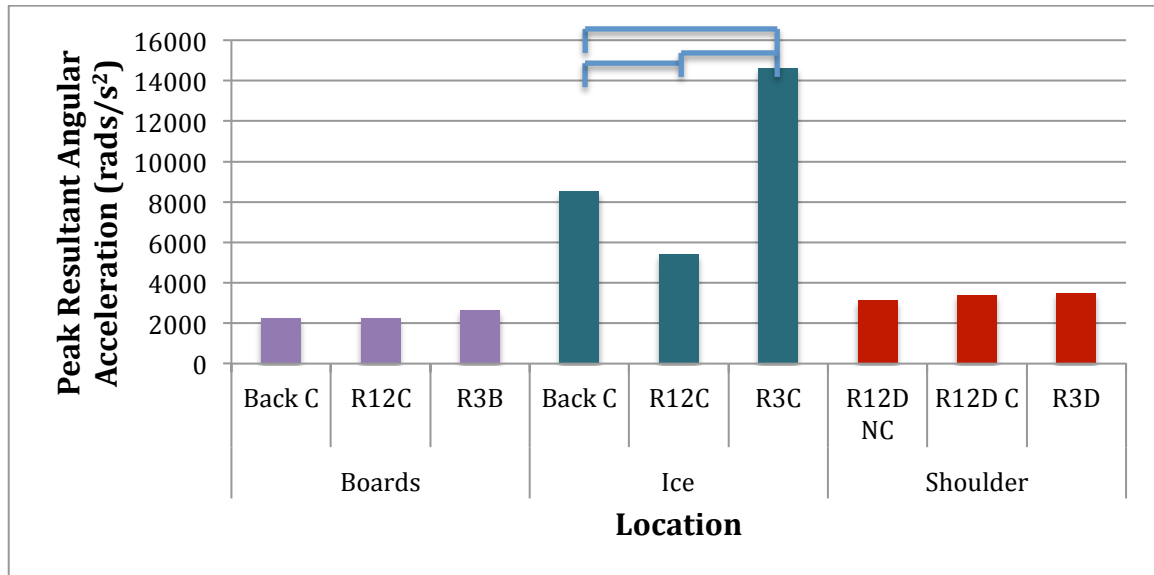


Figure 10: The influence of location on peak resultant angular acceleration for head to boards, head to ice and shoulder to head impact events. Blue square brackets indicate significant differences.

4.1.3.2 Maximum Principal Strain

Further, head to ice falls and shoulder to head collisions resulted in higher maximum principal strain when the impact location was to the side of the head (R3C and R3D respectively) when compared to other locations. However, impact to the back of the head (Back C) resulted in the highest MPS for head to boards events. The head to ice impact to the R3C location resulted in a mean MPS of 0.66 (± 0.07), with the shoulder to head collision to the R3D locations resulted in a mean MPS of 0.31 (± 0.11) and the head to boards impact to the Back C location resulted in a mean MPS of 0.18 (± 0.06) (Figure 11).

A significant main effect was found for location in terms of MPS ($p < 0.01$). Tukey's post hoc test revealed significant differences between all head to ice event locations and all other locations ($p < 0.05$). For shoulder to head collisions R12D non centric ($M = 0.22 \pm 0.04$) was significantly different from both R12D centric ($M = 0.29 \pm 0.08$; $p < 0.05$) and R3D ($M = 0.31 \pm 0.11$; $p < 0.05$), however the R3D location was not significantly different from the R12D centric location ($p = 0.31$). For head to boards all impact locations were significantly different from each other in terms of MPS ($p < 0.05$).

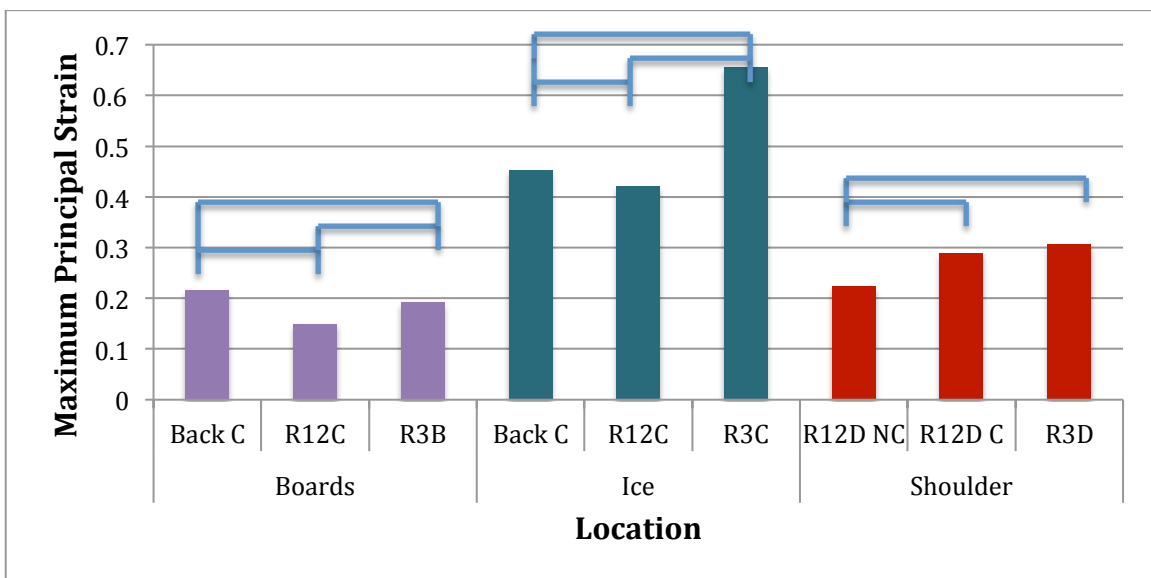


Figure 11: The influence of location on maximum principal strain for head to boards, head to ice and shoulder to head impact events. Blue square brackets indicate significant differences.

5 CHAPTER 5: DISCUSSION

Identifying head impact events in women's hockey and the dynamic response and brain tissue response associated with them can lead to better understanding of which events carry a higher risk of head injury. Research has reported that certain head impact events in women's hockey can lead to concussion (Delaney et al., 2014) and that some head impact events happen more frequently than others (Wilcox et al., 2014). The dynamic and brain tissue response of these head impact events at a range of typical velocities and locations specific to elite women's hockey has not yet been investigated. The objective of this thesis was to characterize distinctive events and the corresponding dynamic and brain tissue responses that are specific to elite women's hockey using reconstructed head impact events.

5.1 Frequency of Head Impact Event

The three most frequent head impact events in women's hockey were found to be head to boards impacts, shoulder to head collisions and head to ice falls. The most frequent head impact event, head to boards, occurred in 40% of the impacts with shoulder to head collisions occurring in 34% of head impacts. When considering the location characteristics of each event type, nine total events were tested at a range of velocities. Figures 12, 13 and 14 depict the peak resultant linear acceleration, peak resultant angular acceleration and maximum principal strain of these nine head impact events as well as the frequency of event found in this study.

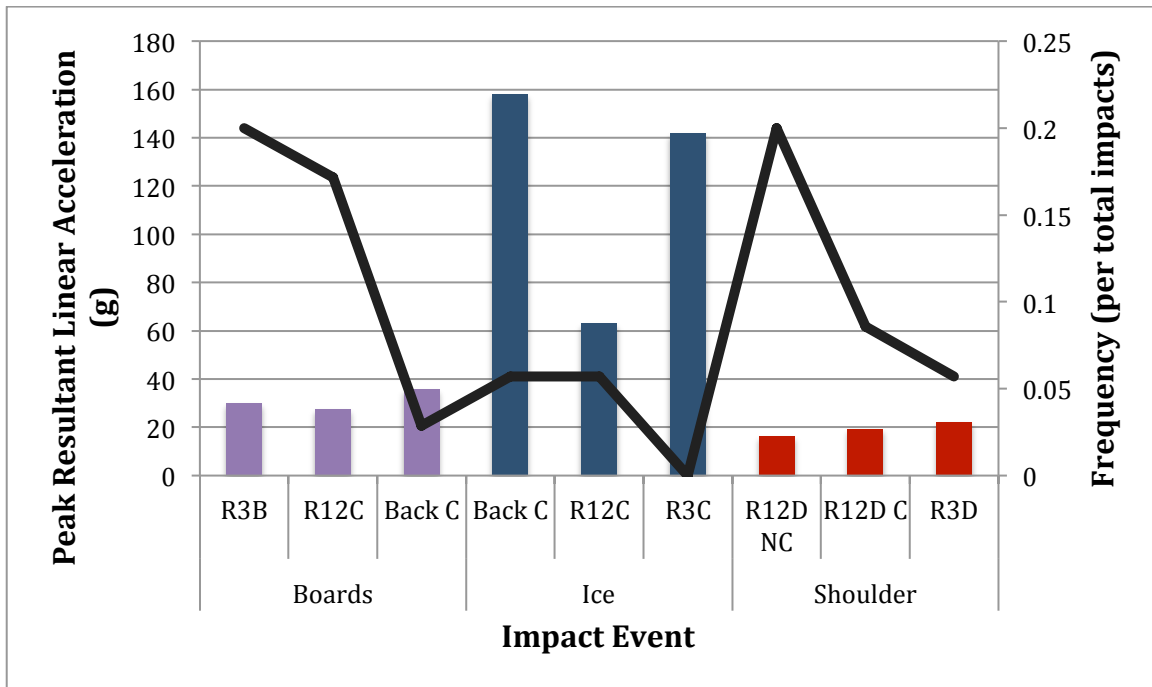


Figure 12: Mean peak resultant linear accelerations for head to boards, head to ice and shoulder to head event conditions impacts at average velocities. The black line represents the frequency of each impact event condition.

The two most frequent events; the head to boards impact event at the R3B (side) location and the shoulder to head collision event at the R12D non centric (front/side) location each accounted for 20% of the overall impact events.

However, these impact events yielded two of the lowest dynamic response results (boards, R3B: 30.1g and 2207 rad/s²; shoulder, R12D NC: 16.4g and 3328 rad/s²).

The head to boards events resulted in values that fall below peak dynamic response of mTBI falls reported by Post et al. (2015). However, the peak resultant angular accelerations of the shoulder to head collisions collected in this study are comparable to the peak angular accelerations of mTBI sport collisions (Post et al., 2015; Rousseau thesis, 2014). Conversely, the three head to ice events represented

only 11% of the impacts collected in this research yet the Back C (back) and the R3C (side) events resulted in peak dynamic responses above those found in mTBI fall data reported by Post and colleagues (2015). These comparisons indicate that shoulder to head collisions in elite women’s hockey may put players at risk of concussion based on their frequency and the peak linear acceleration. While head to ice falls are not as frequent in elite women’s hockey, the magnitude of the dynamic response resulting from these events also indicate a risk of concussion.

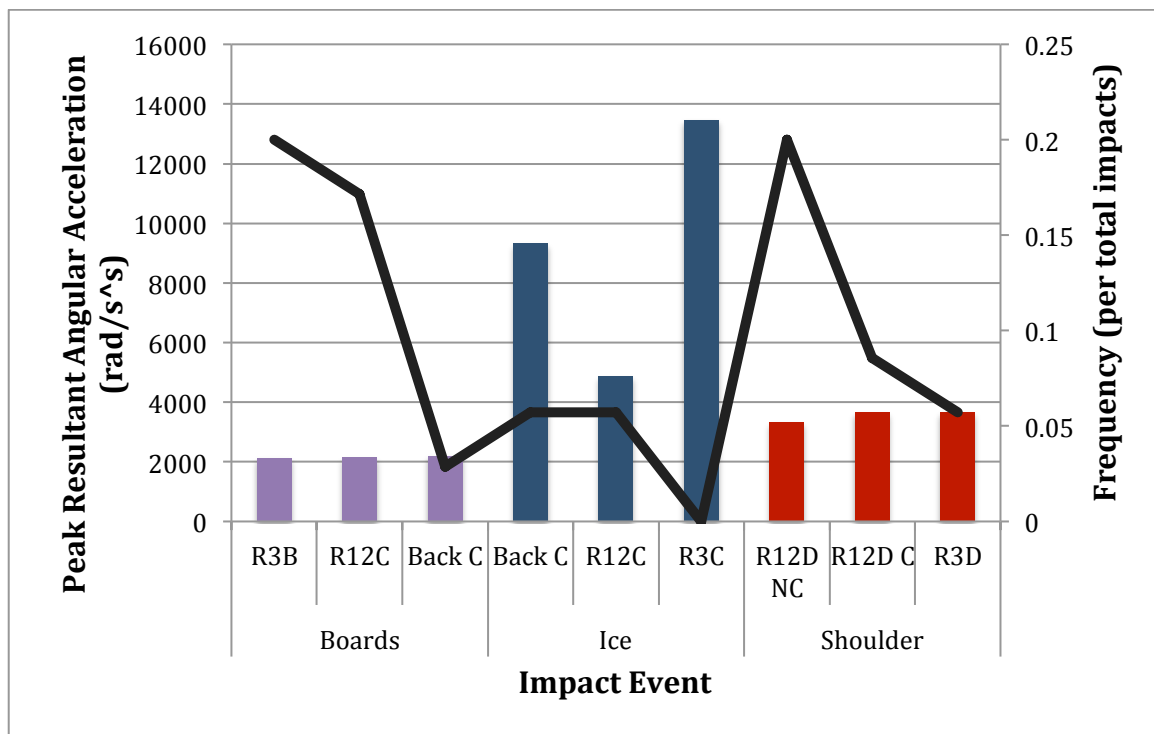


Figure 13: Mean peak resultant angular accelerations for head to boards, head to ice and shoulder to head event conditions impacts at average velocities. The black line represents the frequency of each impact event condition

In terms of MPS, we found a statistical difference between head to boards and shoulder to head impact events, shoulder to head, R12D NC measured higher than head to boards R3B with 0.24 and 0.19 respectively (Figure 14). While these two

head impact locations resulted in relatively low responses when compared to the other head impact events tested, they did create responses that represent a high probability of concussion when compared to concussion threshold research (Zhang et al., 2004). Again, head to ice impacts resulted in significantly higher responses but accounted for only 11% of the head impact events. As a result, both shoulder to head R12D NC collisions events and head to boards R3B head impact events have a high risk of concussion in women’s hockey based on the frequency and biomechanical response measures of these events.

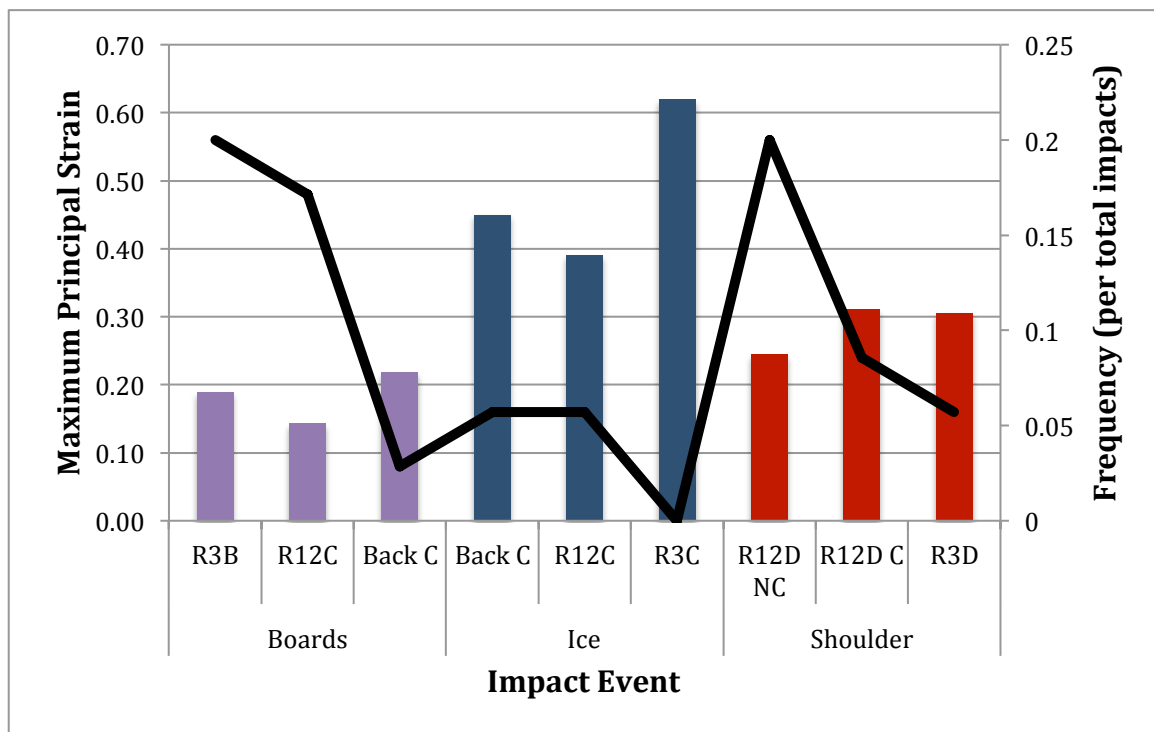


Figure 14: Mean maximum principal strain for head to boards, head to ice and shoulder to head event conditions impacts at average velocities. The black line represents the frequency of each impact event condition.

5.1.1 Dynamic Response

Head to ice falls resulted in significantly higher peak resultant linear acceleration, peak resultant angular acceleration and maximum principals strain when compared to head to boards impacts and shoulder to head collisions. Although the average velocity of a head to ice fall (4.8 m/s) is only slightly greater than the average velocity of a shoulder to head collision (4.6 m/s) the energy transfer characteristics of a fall result in significantly higher dynamic and brain tissue response which corresponds with current research (Hoshizaki et al., 2013). Head to ice impact events typically occur by players falling from their height and not being able to use their arms to protect themselves. In this study, collision velocities were measured by the relative speed between two impacting players. These collisions were in smaller areas of the ice where players were battling for the puck and not reaching high speeds. This could contribute to the average collision velocity being slightly lower than the average head to ice fall velocity. Head to ice falls at 4.8 m/s resulted in an average peak linear acceleration of 97.8 g and an average peak angular acceleration of 9222 rad/s² which measure above the 80% probabilities of concussion reported by Zhang and colleagues (2004). This data is comparable to a study that investigated goaltender hockey falls to the ice using an MEP anvil to simulate the head impacting ice (Clark thesis, 2016). In Clark's study, falls to the MEP anvil at 5 m/s resulted in an average peak linear acceleration of 162.6 g and an average peak angular acceleration of 9275 rad/s². Differences in the peak linear acceleration could be attributed to differences in impact locations as well as

impacting surface. These high results further support the notion that head to ice impact events create high dynamic responses that represent a high risk of injury.

Head to boards impacts and shoulder to head collisions were not found to be significantly different from each other in terms of peak resultant linear acceleration, peak resultant angular acceleration. This is interesting considering the energy transfer characteristics of shoulder to head collisions compared to head to boards impacts are known to be different (Hoshizaki et al., 2013). The non-significant results in this case are likely due to two factors; two of the three locations in the shoulder to head collisions were to the front/side of the head. These two locations represent the “clipping” nature of a shoulder to head collision in hockey. In this case, most of the energy of this collision is maintained in the velocity and mass of the impacting player. In contrast, two of the three locations for head to boards impacts were to the back and side to the head and through the center of gravity of the head. These locations may explain why head to boards impact events had lower rotational accelerations. Secondly, the average velocity of shoulder to head collisions being only 1.6 m/s greater than the average velocity of head to boards impacts likely contributed to the non significant differences in the dynamic responses. Due to less energy being transferred into the head in shoulder to head collisions than head to boards impacts, more energy, thus more velocity, would have to be applied to the collision in order to create a significant difference between the two events. The average peak linear and angular accelerations of average velocity head to boards impacts and shoulder to head collisions collected in this thesis are

below 25% probabilities of concussion as proposed by Zhang and colleagues (2004) and concussion risk thresholds proposed by Fredeche and McIntosh (2009).

Recent studies have reported the dynamic response of women's hockey head impacts using helmets outfitted with accelerometers (Head Impact Telemetry (HIT) system). Wilcox and colleagues (2014) reported the average peak linear acceleration and peak angular acceleration of head contact with another player, ice or boards to range from 26.8g-35.2g and 1859.5-2323.0 rad/s² respectively (Wilcox et al., 2014). A similar study reported the average peak linear and peak angular accelerations of four head impacts that were suspected to result in a concussion diagnosis to be 43±11.5g and 4030±1435 rad/s² respectively (Wilcox et al., 2015). This dynamic response data is comparable to the head to boards impacts and the shoulder to head collision data collected for this thesis. However, the head to ice falls in this thesis are considerably higher than the data reported in these two studies. The authors reported this data in full acknowledgment of the small sample size but concluded that the values collected in this study were lower than those of commonly used concussion threshold values. The author's concluded that these results suggested that women may be at risk for concussion from impacts that produce lower dynamic response values than in men's hockey. The shoulder event data collected in this thesis fall above the peak angular acceleration data collected in Wilcox and colleague's 2014 study. Indicating that elite women's hockey players may be experiencing higher rotational accelerations from player-to-player collisions than previously reported. It is also important to interpret the results of the four

data points Wilcox et al., 2015 study in light of the limitations of the Head Impact Telemetry (HIT) system. The dynamic response reported may be reflective of the motion of the helmet and not necessarily of the motion through the center of gravity of the head. Data collected using instrumented helmets likely gives good indication of the frequency of head impacts but the magnitude of head impact within a hockey setting is still subject to debate (Jadischke et al., 2013; Allison et al., 2013; O'Connor et al., 2017).

5.1.2 Brain Tissue Response

Maximum principal strain is a measure of the stretching brain tissue experiences due to rapid movement of the head and is reflective of the deformation to brain tissue theorized to contribute to concussion symptoms. MPS was the only measure to indicate significant differences between the three head impact events highlighted in the study. Head to ice falls resulted in the highest average maximum principal strain of 0.49 when impacted at the average velocity (4.8 m/s). This result is comparable to research that dropped a goaltender helmeted male headform onto an MEP anvil simulating ice (Clark thesis, 2016). Another study investigated helmeted falls onto an MEP anvil simulating ice at 5.2 m/s and found average MPS to be 0.51 (Kendall thesis, 2016). Both Kendall (2016) and Clark (2016) used a 50th percentile Hybrid III male headform compared to the 5th percentile female hybrid III headform used in this thesis. The similarities between these results indicate that headform size may not have a significant effect on head to ice falls at high velocities (~5 m/s).

Shoulder to head collisions resulted in the second highest average MPS value of 0.29 when dropped at average velocity (4.6 m/s). This value is similar to the average MPS of shoulder to head collisions at 7.3 m/s reported by Kendall (2016) and Clark (2016). The similar result from a significantly lower collision velocity could be explained by the smaller headform used in this thesis in addition to different head impact locations. The average MPS of the average velocity (4.6 m/s) shoulder to head collisions is above the 80% probably of concussion (0.24) proposed by Zhang et al (2004) and the concussion threshold (0.26) proposed by Kleiven (2007). The average MPS found in this thesis (0.29) falls just below the average MPS (0.30) of reconstructions of NHL shoulder to head collisions that caused concussion (Rousseau, 2014). This study proposed that due to the higher compliance of the shoulder pad of a shoulder to head collision (soft material), the impact duration elongates, contributing to a higher MPS (Rousseau, 2014).

Head to boards impacts resulted in the lowest average MPS of the three head impact events with a reported MPS at average velocity (3.2 m/s) of 0.18. This result is similar to the 0.16 MPS value reported by Clark thesis (2016) of a 3.5 m/s helmeted fall to MEP anvil. This MPS result falls above the proposed 25% probability of concussion reported at 0.14 (Zhang et al., 2004).

5.2 Head Impact Characteristics

To understand the risk of injury associated with head impact events in women's hockey a range of velocities and locations were chosen. Videos of each head impact

event were analyzed to determine the velocity of head impact. The average velocity for each impact event, ± 1 m/s were chosen as the three head impact velocities in this study. These velocities represented the range of velocities each head impact event could occur. Video of each event was also analyzed to determine impact location/direction. Velocity and location significantly affected the dynamic response and brain tissue response of head impact events in this study.

5.2.1 Velocity

The results of this thesis demonstrated that increasing velocity significantly increases dynamic response and MPS. Head to ice falls and head to boards impact events significantly increased in terms of peak linear acceleration, peak angular acceleration and MPS as velocity increase from low to average to high. Interestingly, shoulder to head collision events significantly increased in terms of peak linear acceleration, peak angular acceleration and MPS when velocity increased from low to high however, peak linear acceleration and peak angular acceleration did not significantly increase as velocity increased from average to high. This suggests that peak dynamic response of collision events may not be as sensitive to changes in velocity when compared to falls. Also, dynamic response may not increase uniformly as velocity increased. This is consistent with the results of a study involving American football helmets where dynamic response was shown to be similar between impacts of 5.5 m/s and 7.5 m/s, but increase by approximately 40% when velocity was increased to 9.5 m/s (Post et al., 2013).

5.2.2 Location

Impacts to the side of the head produced the highest angular acceleration for all three head impact events and produced the highest MPS for head to ice falls and shoulder to head collisions. These results along with the high frequency of reported concussions from hockey head impacts to the side of the head (Delaney et al., 2014) indicate that side impacts have a higher risk for causing concussions. It is important to note that falls to the ice impacting the side of the head is a low frequency event. This is because as players fall onto their side, their shoulder impacting the ice will likely rotate the body onto its front or its back before the head impacts the ice. Also, head to ice falls to the front/side (facemask) resulted in a lower peak linear acceleration, peak angular acceleration and MPS. These impacts caused the facemask to deform, absorbing some of the impact energy. This is likely the reason why falls to the facemask resulted in lower responses.

Interestingly, none of the head to boards impacts or the shoulder to head collisions locations produced significantly different angular accelerations. The non-significant results for head to boards impacts could be due to the relatively low impact velocities used in this study. For example, if the same locations were impacted at higher velocities there may be a larger separation of results between locations. The head to ice fall events that were impacted at higher energy levels and resulted in significant differences between locations demonstrate these differences. For the shoulder to head collisions, low impact velocities as well as the high compliance of

the shoulder pad could have masked the effect of impact location for dynamic response.

6 CHAPTER 6: CONCLUSION

The high frequency of concussion in women's hockey has become a growing concern amongst researchers, medical professionals and the hockey community. The majority of concussions in women's hockey are a result of three head impact events: Head to ice falls, head to boards impacts and shoulder to head collisions. This study investigated the dynamic response and brain tissue response of these three head impact events across the velocities and locations they can occur at. The objective of this study was to better understand the risk of head injury associated with these distinct head impact events in light of how frequent each occurs and the corresponding severity of the dynamic response and brain tissue strain.

Each head impact event created unique brain tissue strains however; head to boards impacts produce similar dynamic response results to shoulder to head collision events. Head to ice fall events resulted in significantly higher dynamic responses and brain tissue strains, well above reported 50% risk for mTBI values. However, head to ice falls occurred significantly less frequently than shoulder to head collisions and head to boards impacts in elite women's hockey. While players do not experience head to ice contact often, when they do they should be considered a high

risk for concussion. Both head to boards impacts and shoulder to head collisions resulted in brain tissue responses similar or above reported 50% risk for mTBI. Increasing impact velocity resulted in an increased dynamic response of the head and brain tissue strain. Interestingly, changing impact location only resulted in significant differences within the head to ice impact events. Overall, this study describes dynamic response of the head and brain tissue strains for head to boards impacts, head to ice falls and shoulder to head collisions; the impacts that frequently occur and the observed impact velocities and locations. Future research should investigate head impacts in elite women's hockey that result in concussion to give a better understanding of the tolerance ranges of head impacts that can lead to head injury. In conclusion, head to boards, head to ice and shoulder to head impacts all occur in women's hockey, however, the frequency and biomechanical response of these events provide different pictures of head injury risk. The results of this study indicate that it is important to consider both the frequency and impact characteristics when evaluating the risk of head injury in women's hockey.

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APPENDIX

Table 12: Mean peak dynamic response and maximum principal strain (± 1 standard deviation) of high incidence (most frequent) head impact location, medium incidence (second most frequent) head impact location and low incidence (third most frequent head impact location for head to boards event at a range of common velocities.

	Velocity	Linear	Angular Acceleration	
Location	(m/s)	Acceleration (g)	(rad/s²)	MPS
High	2.2	23.1 (0.41)	1828 (38)	0.13 (.01)
Frequency	3.2	30.1 (0.87)	2133 (90)	0.19 (.02)
(R3B)	4.2	44.7 (2.3)	4004 (233)	0.26 (.00)
Medium	2.2	22.6 (2.3)	1249 (68)	0.11 (.01)
Frequency	3.2	27.6 (2.2)	2194 (278)	0.14 (.02)
(R12C)	4.2	45.7 (1.1)	3411 (972)	0.20 (.04)
Low	2.2	25.9 (0.4)	1525 (158)	0.16 (.02)
Frequency	3.2	35.7 (0.7)	2207 (97)	0.22 (.00)
(Back C)	4.2	51.4 (0.6)	2955 (549)	0.27 (.01)

Table 13: Mean peak dynamic response and maximum principal strain (± 1 standard deviation) of high incidence (most frequent) head impact location, medium incidence (second most frequent) head impact location and low incidence (third most frequent head impact location for head to ice events at a range of common velocities.

	Velocity	Linear	Angular Acceleration	
Location	(m/s)	Acceleration (g)	(rad/s²)	MPS
High	3.8	124.5 (3.9)	6748 (160)	0.37 (.00)
Frequency	4.8	158.0 (6.5)	9325 (560)	0.45 (.02)
(Back C)	5.8	183.6 (6.2)	9508 (2630)	0.54 (.01)
Medium	3.8	56.2 (1.5)	3665 (312)	0.32 (.02)
Frequency	4.8	63.1 (2.4)	4875 (443)	0.39 (.05)
(R12C)	5.8	89.5 (0.7)	7674 (404)	0.56 (.03)
Low	3.8	112.7 (3.8)	12466 (500)	0.61 (.01)

Frequency	4.8	141.9 (3.3)	13466 (839)	0.62 (.03)
(R3C)	5.8	182.7 (3.6)	17937 (1019)	0.73 (.04)

Table 14: shows the peak resultant linear acceleration, peak resultant angular acceleration and maximum principal strain results of head to boards impact events across three impact locations and three impact velocities found to be common to this impact event.

Location	Velocity (m/s)	Linear Acceleration (g)	Angular Acceleration (rad/s²)	MPS
High	3.6	11.0 (0.1)	2256 (38)	0.17 (.00)
Frequency	4.6	16.4 (0.5)	3328 (170)	0.24 (.01)
(R12D non- centric)	5.6	20.6 (0.4)	3844 (215)	0.25 (.01)
Medium	3.6	13.7 (0.1)	2432 (34)	0.2 (.01)
Frequency	4.6	19.4 (1.6)	3668 (439)	0.31 (.02)
(R12D centric)	5.6	21.3 (0.5)	4089 (267)	0.36 (.03)
Low	3.6	16.9 (0.3)	2207 (59)	0.2 (.01)
Frequency	4.6	22.3 (0.3)	3671 (89)	0.31 (.00)
(R3D)	5.6	26.4 (0.4)	4576 (40)	0.42 (.01)