A Comparison Between Pee Wee and Bantam Youth Ice Hockey Brain Trauma Profiles

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Abstract

There is an increasing concern surrounding brain trauma risks for young athletes participating in contact sports, as brain injuries in youth have detrimental consequences on their cognition, behaviour, and learning abilities (Ayr et al., 2009; Yeates and Taylor, 2005). Given the potential for future neurological and mental health issues, there is further need to quantify brain trauma within youth sport populations (Daneshvar et al., 2011). Ice hockey is a sport with high rates of brain injury in youth, and the shift from Pee Wee (ages 11-12) to Bantam (ages 13-14) hockey is an important transition period in which athletes are introduced to body checking (Black et al., 2017; Marar et al., 2012). The purpose of this study was to compare the brain trauma profiles between Pee Wee and Bantam hockey in terms of the head dynamic response, brain tissue deformation, and frequency of head impact events.

Head impact events from 16 Pee Wee and 16 Bantam hockey games were analyzed, and 71 exemplar impact reconstructions were conducted. No differences were found between Pee Wee and Bantam for magnitudes of peak linear acceleration, peak rotational acceleration, or maximum principal strain (MPS). Overall frequency of head impact events was also similar between the two groups. However, chi-squared tests found that the type of head impact event was significantly associated with the age group (X^2 (6) = 17.699, p = 0.006, φ_c = .347). Ice and boards head impact events were more frequent in Pee Wee, while shoulder and glass head impact events were more frequent in Bantam. There were slightly higher frequencies of events ≥26% MPS reported in Pee Wee. However, events were more frequently within the 17-25.9% MPS range for Bantam and were typically the result of shoulder to head impacts.

While head impact events at younger ages are more accidental in nature, deliberate player contact from body checking is associated with greater risks for sustaining brain trauma. Policymakers should consider whether Bantam is the most appropriate age to continue allowing for body checking. Developing age-specific helmet technology may be an effective method for protecting against the unique brain trauma risks which are associated with different levels of youth hockey competition. Understanding the characteristics of how brain trauma occurs within youth hockey can help inform and guide future protective and preventative strategies to keep participation in this sport safe for all athletes.

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CHAPTER 1: INTRODUCTION

1.1 Problem Statement

Parents are becoming increasingly concerned about the potential brain injury risks for their children participating in recreational and competitive sports (Bloodgood et al., 2013; Lin et al., 2015). Brain injuries have been shown to have detrimental effects on cognitive function, memory, behaviour, and learning abilities in youth (Ayr et al., 2009; Daneshvar et al., 2011; Moser et al., 2005; Yeates and Taylor, 2005). Brain trauma also poses important implications for public health, as this has been associated with increased risks for mental health problems, such as anxiety and depression (Chrisman and Richardson, 2014; Guskiewicz et al., 2007a; Kontos et al., 2012; Max et al., 2012; Rapoport et al., 2003). Issues following brain injury in youth affect academic performance, reduced quality of life, as well as parental and family burdens (Ganesalingam et al., 2008; Moran et al., 2012; Ransom et al., 2015). With recent high-profile incidents involving the suicides of retired professional athletes, there has been an increase in investigations regarding the long-term impacts of sport-related brain trauma in youth.

Concussion symptomology is often variable and head impacts can lead to cognitive and neurological deficits even when clinically asymptomatic (Gavett et al., 2011). Sub concussive head impacts without clinical signs of concussion may still have lasting effects on neurological function and brain health (Daneshvar et al., 2011; McCrory, 2011). Exposure to repetitive sub concussive brain trauma has been identified as a contributing factor for the development of chronic traumatic encephalopathy (CTE), a neurodegenerative disease which has been identified post-mortem in former athletes from contact sports (Baugh et al., 2012; Gavett et al., 2011; McCrory, 2011; McKee et al., 2013). There is no in-vivo diagnosis of CTE and there is a lack of longitudinal studies assessing direct causative links between brain trauma exposure and CTE pathogenesis (McCrory et al., 2013). However, retired professional athletes with multiple concussions are significantly more likely to have cognitive impairments, memory dysfunction, incidence of depression, and earlier onsets of neurological disorders (Esopenko et al., 2017; Guskiewicz et al., 2005; 2007a). Similar declines to cognition and brain health in later life have also been documented among non-professional athletes with a history of concussion from collegiate-level contact sports (De Beaumont et al., 2009; Tremblay et al., 2014).

Although sub concussive head impacts may not produce clinically-evident symptoms of concussion, these types of impacts can still lead to cellular damage, neurophysiological changes, and neurometabolic cascades that contribute to the pathology of CTE (Baugh et al., 2012; Gavett et al., 2011). Both youth and adult athletes exposed to repetitive sub concussive head impacts in contact sports have been found to demonstrate significant changes to their cerebral white matter (WM) structure and functioning, often without any reported symptoms of concussion (Bazarian et al., 2014; Breedlove et al., 2012; Davenport et al., 2014; McAllister et al., 2014). This poses important implications for brain health, as changes to WM integrity have been directly associated with cognitive and behavioural impairments, neuronal volume loss, and brain degeneration (Bigler, 2008; Guild and Levine, 2015; Huh et al., 2008; Kraus et al., 2007; Niogi et al., 2008; Pullela et al., 2006). However, it still remains unclear what the exact role of factors, such as head impact magnitudes or impact frequencies, may have on the development of brain health issues or neurological disorders (Baugh et al., 2012; Gavett et al., 2011).

Youth hockey is described as having high rates of brain injuries, with head impacts typically occurring from falling or collision events (Emery and Meeuwisse, 2006; Hutchison, 2011). Each represent unique impact events with different biomechanical responses and risks for brain injury (Kendall, 2016). Exposure to types of impact events, impact magnitudes, and impact frequencies also change as children develop physically into adolescence. Brain trauma risks change as these youth become larger, faster athletes, as both the impact mass and velocity are important characteristics which can influence head impact magnitudes (Post and Hoshizaki, 2012). The shift from Pee Wee (ages 11-12) to Bantam (ages 13-14) hockey is an important transition period where youth are introduced to body contact from checking, while beginning to exhibit considerable anthropometric variability within age groups (Fryar et al., 2012). Recent policy changes were made to start body checking at Bantam and adopt zero-tolerance rules for head contact in youth hockey. While removing body checking from Pee Wee has been reported to be effective for reducing the incidence of brain injuries at this level (Black et al., 2006; 2017), both Pee Wee and Bantam athletes are still described as having high risks for sustaining game-related brain trauma (Krolikowski et al., 2017). Different athlete sizes, skill levels, and playing rules all contribute towards creating competition environments with varying exposure to head impact events (Emery et al., 2010a; Wattie et al., 2007). Therefore, these factors can influence the differing risks for brain trauma which are associated with youth hockey participation at various ages of play.

Given the potential injury, but relatively unknown influence that head impacts can have on brain health throughout life, there is a need to better describe the effects of brain trauma exposure within youth sport populations (Baugh et al., 2012; Daneshvar et al., 2011). Researchers have used head impact telemetry systems to document the cumulative exposure to head impact accelerations in youth contact sports (Broglio et al., 2011; Martini et al., 2013). However, this methodology only captures a part of the trauma contributing to brain injury risk, and has been reported to have limited clinical applicability due to poor sensitivity and specificity for identifying concussive injury (O’Connor et al., 2017). Impact reconstructions have been used in other brain trauma research to describe the head accelerations and brain tissue deformation occurring across a wide range of brain injuries (Dawson, 2016; Doorly and Gilchrist, 2006; Oeur et al., 2015; Post et al., 2015). Existing research characterizing the head impact events contributing to brain trauma risks in hockey have been useful for guiding preventative and protective strategies (Kendall et al., 2012a; Kendall et al., 2014; Nur et al., 2015; Rousseau et al., 2014). However, this type of research has primarily been conducted within adult hockey populations. Youth have been described as having different risks for brain trauma than adults, and the playing environment in hockey can vary depending on the age of play (Dawson, 2016; Wattie et al., 2007). The purpose of this study was to describe the head dynamic response, brain tissue deformation, and frequency of head impact events experienced by competitive Pee Wee and Bantam-level hockey players, and to provide a comparison of the brain trauma profiles between these two age categories of competition.

1.2 Research Question

What are the differences in brain trauma profiles between Pee Wee and Bantam competitive ice hockey, as characterized in terms of the head dynamic response, brain tissue deformation, and frequency of head impact events?

1.3 Objectives

1. To compare the magnitude of peak linear accelerations and peak rotational accelerations from head impact events between Pee Wee and Bantam hockey.
2. To compare the magnitude of maximum principal strains from head impact events between Pee Wee and Bantam hockey.
3. To describe the frequency of head impact events, and the frequency of head impact events per 1000 player-hours, in Pee Wee and Bantam hockey.

1.4 Variables

1.4.1 Independent Variables

1. Age (n = 2)
    - Pee Wee (11-12 years old)
    - Bantam (13-14 years old)
2. Head Impact Event Type (n = 6)
    - Head to ice
    - Shoulder to head
    - Elbow to head
    - Head to head
    - Head to boards
    - Head to glass

1.4.2. Dependent Variables

1. Dynamic Response
    - Magnitude of peak linear accelerations
    - Magnitude of peak rotational accelerations
2. Brain Tissue Deformation
    - Magnitude of maximum principal strains (MPS)
3. Frequency
    - Of head impact events per 1000 player-hours
    - Of MPS magnitudes from head impact events, in terms of MPS categories:
        - Very low: < 8.0%
        - Low: 8.0-16.9%
        - Medium: 17-25.9%

- High: 26-34.9%
- Very high: > 35%

1.5 Experimental Hypothesis

1. Bantam hockey will have significantly greater peak linear acceleration magnitudes from head impact events when compared to Pee Wee hockey.
2. Bantam hockey will have significantly greater peak rotational acceleration magnitudes from head impact events when compared to Pee Wee hockey.
3. Bantam hockey will have significantly greater MPS magnitudes from head impact events when compared to Pee Wee hockey.
4. Bantam hockey will have a significantly greater frequency of head impact events per 1000 player-hours when compared to Pee Wee hockey.
5. The age of play will be significantly associated with the type of head impact events.
6. The age of play will be significantly associated with the frequency of MPS magnitudes.

1.6 Null Hypothesis

1. Peak linear acceleration magnitudes from head impact events will not be significantly different between Pee Wee and Bantam hockey.
2. Peak rotational acceleration magnitudes from head impact events will not be significantly between Pee Wee and Bantam hockey.
3. MPS magnitudes from head impact events will not be significantly different between Pee Wee and Bantam hockey.
4. The frequency of head impact events per 1000 player-hours will not be significantly different between Pee Wee and Bantam hockey.
5. The age of play will not be associated with the type of head impact events.

6. The age of play will not be associated with the frequency of MPS magnitudes.

1.7 Limitations

1. Head impacts in this study were logged and analyzed from in-game video footage. The video image may not have captured all of the impacts due to poor picture quality, blocked camera angles, or impacts which occurred outside of the field of view. This likely resulted in a lower number of confirmed head impact events and underrepresentation of the head impact frequencies.
2. The Hybrid III headform used in this study was not designed to be biofidelic (Kendall et al., 2012b). The 1-inch skinform and rigidity of this headform may have resulted in lower head acceleration values and reduced variance than those found with real-life impacts (Seeman et al., 1986). However, the Hybrid III headform has been used in existing literature as an appropriate surrogate for assessing head impact kinematic responses and head injury risks in sports (Kendall, 2016; Pellman et al., 2003; Zhang et al., 2004).
3. The finite element model used in this study was the University of College Dublin Brain Trauma Model (UCDBTM), which was developed and validated using neuroimaging scans of an adult male cadaver (Horgan and Gilchrist, 2003). While this may not be fully representative of the adolescent brain, research has suggested that adolescent brain tissue characteristics still remain within the ranges for that of an adult brain (Chatelin et al., 2010; Roth et al., 2009).
4. MPS values from the UCDBTM represented peak strain levels across each of the three axes (x,y,z). While this did not provide a global representation of the strain experienced by the brain during inertial loading, MPS has been widely used in previous research for characterizing brain injury risks resulting from sport-related head impacts (Kendall, 2016;

McAllister et al., 2012; Rousseau, 2014; Zhang et al., 2004).

1.8 Delimitations

1. Only video footage from in-game competitions were used in this study, as brain injuries in youth hockey have been reported to occur more frequently during games than practices (Schmidt et al., 2016; Stuart et al., 1995; Willer et al., 2005). The video was collected from competitive hockey teams within the Ontario and Quebec regions, which may not be fully representative of hockey in other parts of Canada or the world.
2. Game times from the videos used in this study were not of consistent lengths and only the actual time on ice recorded on film was used. Therefore, frequency analyses were standardized to 1000 player-hours and the reporting terminology '*per analysis*' was used in lieu of '*per game*'.
3. Due to limitations related to video quality, logged events were divided into '*confirmed*' and '*suspected*' head impacts as fully described in Section 3.3.1. However, a '*combined*' count including both confirmed and suspected head impacts was also included in certain aspects of the frequency analyses.
4. Head impact events involving contact with the knee, hip, stick, or chest were excluded from this study. Head impact events involving punches and pucks were not included for exemplar impact reconstructions or magnitude analyses.
5. A child-specific finite element model does not currently exist within the literature. Therefore, the finite element model used in this study was a 95% scaled version of the adult UCDBTM, which was selected based on its correlation to existing MRI research describing the size and geometry of male adolescent brains (Mennes et al., 2014; Post et al., 2017).

1.9 Significance

Sport-related concussive brain injury have been extensively documented in the current literature. However, sub concussive head impact events, and its associated brain tissue trauma, within contact sports remains relatively unknown. Given the potential physical, cognitive, and mental health implications that this can have for athletes, it remains important to understand how brain trauma may occur at different levels of competition. With research also implicating a possible link between repetitive sub concussive head impacts to brain health sequelae, there is a need to investigate this type of trauma within the context of youth sports (Baugh et al., 2012; Daneshvar et al., 2011). This research conducted physical reconstructions of head impacts events in Pee Wee and Bantam hockey to characterize and compare the brain trauma profiles between these two age groups. This provides further insight into the brain tissue trauma that youth experience when participating in high-risk contact sports, such as hockey. By improving our understanding of how brain trauma occurs within these sporting environments, it can help better inform protective and preventative strategies.

CHAPTER 2: REVIEW OF LITERATURE

2.1 Injury in Youth Hockey

Hockey is a popular sport in North America, with over one million youth players (146,102 Pee Wee, 132,431 Bantam) registered across Canada and the United States during the 2016-2017 season (Hockey Canada, 2017; USA Hockey, 2017). Hockey has been identified as having some of the highest rates of head injury in youth sports (Emery and Meeuwisse, 2006; Guerriero et al., 2012). Head injuries account for 20-24% of all injuries that occur in youth hockey and this injury risk is shown to increase with age as players become bigger, faster, and stronger athletes (Emery and Meeuwisse, 2006; Marar et al., 2012; Meehan et al., 2011; Willer et al., 2005). This is consistent with both Canadian hospital injury data and Hockey Canada Insurance data indicating that older athletes sustain more injuries than their younger counterparts, particularly at higher levels of competitive hockey (Wattie et al., 2007). Both Pee Wee and Bantam-aged players are significantly more likely to suffer a concussion than their younger counterparts (Emery and Meeuwisse, 2006). Emery and Meeuwisse (2006) also reported that the rates of concussion injury were 1.25 times higher in Bantam hockey (0.97 per 1000 player-hours) with respect to Pee Wee hockey (0.81 per 1000 player-hours).

Youth also exhibit significant anthropometric variability throughout adolescence (de Onis and Habicht, 1996; Fryar et al., 2012). The average weight of an American child ranges between 47-52 kg in youth aged 11-12, and 59-64 kg in youth aged 13-14 (Fryar et al., 2012). Large disparities in athlete size has been identified as a contributing factor to the prevalence of head injury in youth hockey (Brust et al., 1992; Emery and Meeuwisse, 2006; Mölsä et al., 2003; Stuart et al., 1995). Differences of more than 48-59 kg in weight have been documented between the smallest and largest players at both Pee Wee and Bantam levels of hockey (Brust et al., 1992;

Emery and Meeuwisse, 2006; Stuart et al., 1995). This has implications for brain injury recovery, as lighter athlete weights have been associated with increased risks for longer concussion symptom durations among male youth hockey players (Kriz et al., 2016). Additionally, Kriz et al. (2016) evaluated the physical maturity and pubertal stage of concussed hockey athletes in their study and also found that males who were in early stages of puberty had concussion symptoms lasting significantly longer than those who were in later stages of puberty.

As youth participation in hockey continues to grow across North America each year (Hockey Canada, 2017; USA Hockey, 2017), more young athletes will be exposed to the potential risks for brain trauma. Athlete age has been reported to have an influence on the prevalence and severity of brain injuries in youth hockey, and thus it remains important to consider the potential factors which contribute towards sustaining brain trauma at differing ages of competition within this sport (Mölsä et al., 2003; Wattie et al., 2007; Willer et al., 2005).

2.2 Body checking in Youth Hockey

Body checking has been reported to be associated with significant increases to head injury risk in youth hockey players, with considerable debate regarding the age to introduce body checking and still keep the sport safe for participants (Emery et al., 2010b; King and Leblanc, 2006; Marchie and Cusimano, 2003; Warsh et al., 2009). 45-86% of injuries in youth hockey have been reported to result from body checking, which has also been linked with a nearly 2-fold increase to concussion risk (Emery and Meeuwisse, 2006; Emery et al., 2010a; Warsh et al., 2009). Among Pee Wee hockey players, the rate of concussion has been reported to be 3.75 times higher in body checking leagues than in leagues that did not allow body checking (Black et al., 2016; Emery et al., 2010b). In light of this information, Hockey Canada implemented zero-tolerance rules for head contact starting in 2011 for youth hockey. This was followed by policy changes in

2013 to begin introducing body checking at the Bantam, rather than Pee Wee level.

Early evidence comparing concussion rates in Pee Wee hockey before and after this body checking rule change has shown a relative decrease of 64%, and an estimated reduction of 4806 concussions (95% CI: 2791-6791) in one season across Canada (Black et al., 2017). However, a separate study conducted in Pee Wee and Bantam hockey found that the overall incidence of concussion increased significantly since the 2011 implementation of zero-tolerance head contact rules across Canadian youth hockey leagues (Krolikowski et al., 2017). When comparing brain injury data from before and after this policy change, the risks for in-game concussions were reported to be 1.85 times higher in Pee Wee and 2.48 times higher in Bantam. Krolikowski et al. (2017) also found that Pee Wee and Bantam players had a 4.12 times and 7.91 times increase in respective risk for sustaining more severe concussions (as defined by time loss >10 days). These increases in reported concussion incidence may be partially related to a growing body of awareness among the lay population, as well as more conservative approaches to returning to play following concussion (Bloodgood et al., 2013; McCrory et al., 2017). Nevertheless, despite the adoption of these recent policy changes, the risks for potential brain trauma still remains high in both Pee Wee and Bantam-level hockey. Bantam athletes are being reported as having similar, but relatively greater risks for injury in comparison to Pee Wee athletes, which may be associated with the inclusion of body checking at this level of play (Black et al., 2017; Emery et al., 2010b).

2.3 Brain Injury in Youth

Youth have been shown to be more vulnerable to prolonged difficulties recovering from brain injuries, such as concussion (Field et al., 2003; Pellman et al., 2006; Zemek et al., 2013). A recent study conducted on adolescent athletes (mean age: 15.4 ± 1.5 yrs) who suffered a concussion while playing hockey found that 48% of these athletes experienced symptoms for ≥ 28 days, with average clinical symptoms lasting for 44.5 days (Kriz et al., 2016). Of these hockey players, 35.2% had symptoms up to 3 months post-injury and 13.1% experienced symptoms persisting over 3 months (Kriz et al., 2016). Youth have been shown to experience significant deficits to their attention, information processing, and reaction times when assessed using standardized neuropsychological tests following a head injury (Ayr et al., 2009; Baillargeon et al., 2011; Moser and Schatz, 2002; Sim et al., 2008). Concussed youth demonstrate prolonged impairments to their verbal, visuospatial, and working memory in comparison to adults (Baillargeon et al., 2012; Sim et al., 2008). Asymptomatic children with normal neurocognitive test scores following head injury have also been reported to exhibit behavioural difficulties in the months to years following injury (Ponsford et al., 1999; Yeates and Taylor, 2005). The impacts of these issues have been cited to contribute to the greater academic problems, increased family burdens, and lower quality of life often reported after brain injury in youth populations (Ganesalingam et al., 2008; Moran et al., 2012; Ransom et al., 2015).

Differences in brain injury risks and consequences between youth and adults may be partially attributed to the stages of their physiological growth. A youth brain is less physically mature than that of an adult, and youth are still learning important cognitive skills such as information processing, problem solving, memory consolidation, and concentration (Hunt and Ferrara, 2009). The frontal lobe and prefrontal cortex of the brain are responsible for many of these cognitive skills and other executive function behaviours, which undergo significant maturation throughout adolescence into early adulthood (Luna et al., 2004; Luna et al., 2010; Passler et al., 1985). Brain trauma during this critical development period may contribute to the greater cognitive deficits and more difficult recoveries seen in youth (Guskiewicz and Valovich McLeod, 2011). Given that youth may be particularly vulnerable to the detrimental effects associated with brain trauma, it is important to investigate these risks in relation to youth contact sports (Daneshvar et al., 2011). As these brain injury risks differ from that of adults (Dawson, 2016), gaining a better understanding of brain trauma exposure within the context of youth sport populations can help guide future strategies to protect young athletes participating in high-risk sports such as hockey.

2.4 Sub concussive Brain Trauma

2.4.1 Implications for Brain Health

Issues regarding brain injury management are becoming particularly concerning given a growing body of literature around the effects of sub concussive head impacts on brain health. Repetitive sub concussive head impacts, even without symptoms of concussion, can still create trauma to the brain tissue resulting in cognitive deficits, intercellular disruptions, and changes to the tissue structure (Gavett et al., 2011; McCrory, 2011). In one study conducted on youth football, half of the athletes exhibiting no clinical signs of concussion were still found to have significantly lower in-season verbal and/or visual memory scores when compared to their respective pre-season baselines (Talavage et al., 2014). These athletes were shown to have levels of cognitive impairment which was similar to, or exceeding that of athletes who had been clinically diagnosed with concussion. This also correlated with functional disruptions and significantly decreased activation levels of the brain regions governing memory, behaviour, and emotional regulation (Breedlove et al., 2012; Talavage et al., 2014).

White matter (WM) diffusivity is often used as a means for assessing microstructural WM and axonal damage associated with brain trauma (Alexander et al., 2007; Basser and Jones, 2002). Measures of impaired cognition, memory, and executive function have been closely correlated to WM damage to neural pathways in the brain (Kraus et al., 2007; Niogi et al., 2008). Mild traumatic brain injuries (mTBI) are reported to be associated with decreased WM diffusivity in the corpus callosum, superior longitudinal fasciculus, corticospinal tract, and sagittal stratum brain structures (Kraus et al., 2007; Niogi et al., 2008). Of particular concern is that similar WM changes have also been found from exposure to repetitive sub concussive head impacts in contact sports. In both youth and adult populations, changes to WM diffusivity have been reported within these brain structures following repetitive non-concussive head impacts sustained over the course of hockey or football seasons (Bazarian et al., 2014; Davenport et al., 2014; Koerte et al., 2012; McAllister et al., 2014). In one youth study, changes in the WM diffusivity were found to be over 3 times greater in contact sport athletes when compared to non-athletic controls, and more closely resembled the WM changes identified with clinically diagnosed concussion (Bazarian et al., 2012). These findings have implications for the development of future brain health issues in youth contact sports (Daveshvar et al., 2011; McCrory, 2011). MPS values resulting from concussive and non-concussive head impacts have been correlated with changes to the WM integrity in subcortical brain structures and neural pathways (Ji et al., 2015; McAllister et al., 2012). Given its potential for short- and long-term neurological consequences, this emphasizes the importance of examining sub concussive head impacts in contact sports and characterizing the brain trauma exposure for young athletes.

2.4.2 Chronic Traumatic Encephalopathy

Chronic traumatic encephalopathy (CTE) is a neurodegenerative disease, which has been identified in the brains of deceased athletes participating in contact sports. CTE is a progressive tauopathy characterized by the aggregation and deposition of hyperphosphorylated tau proteins and TAR DNA-Binding Protein 43 throughout the brain (McKee et al., 2013). CTE is associated with diffuse neuronal loss from the atrophy of subcortical WM structures including the corpus callosum, basal ganglia and cerebellum, and neurodegeneration of the septum pellucidum, frontal lobe, and temporal lobe (Gavett et al., 2011; McKee et al., 2013). This disease can manifest as a wide array of progressive neurological impairment and cognitive dysfunction including behavioural disorders, gait and speech abnormalities, attention and memory loss, and dementia (Baugh et al., 2012; McCrory, 2011). CTE has also been associated with mental health issues including severe anxiety, depression, and risk of suicide (Baugh et al., 2012). CTE can only be diagnosed post-mortem and there are no clinically available diagnostic tools to screen for this disease (Baugh et al., 2012). Compounding this problem is a lack of conclusive evidence regarding potential risk factors for the development of CTE. It has been suggested that repetitive sub concussive brain trauma contributes to the neurophysiological changes and neurometabolic cascades leading to CTE pathology (Baugh et al., 2012; Gavett et al., 2011; McCrory et al., 2013). Retired professional and non-professional athletes with past concussions from contact sports have already been demonstrated to experience greater cognitive declines and incidence of neurological disorders in later life (De Beaumont et al., 2009; Guskiewicz et al., 2005; Tremblay et al., 2014). Brain trauma has also been associated with the development of mental health issues such as depression, as both youth and adult athletes with a history of concussion have been reported to be over three times more likely to suffer from depression in later life (Chrisman and Richardson, 2014; Guskiewicz et al., 2007a).

However, it remains unclear what factors or aspects of brain trauma exposure influence these risks for brain health issues. Further research needs to be conducted to characterize potential risk factors for brain trauma, such as the impact magnitudes and frequencies of repetitive sub concussive head impacts in contact sports such as hockey (Baugh et al., 2012; Daneshvar et al., 2011; Gavett et al., 2011). Biomechanical research describing forces acting on brain during head impacts have been shown to be a useful tool for predicting risks for a wide range of potential brain injuries, including concussion, skull fractures, and subdural hematomas (Meaney and Smith, 2011; Oeur et al., 2015; Post and Hoshizaki, 2012). Characterizing the head impact kinematics and brain tissue strains of sub concussive head impacts will help to quantify and describe the brain trauma burdens experienced by youth athletes participating in contact sports such as hockey.

2.5 Head Impact Biomechanics

2.5.1 Linear Acceleration

Linear acceleration has been correlated with increased intracranial pressure gradients resulting from relative brain-skull motions (Gurdjian, 1975; Holbourn, 1943; Thomas et al., 1966). These transient increases in intracranial pressure create shear stresses in the brain tissue, reported in cadaveric studies and animal studies involving adult monkeys (Gurdjian et al., 1961; 1966; Nusholtz et al., 1987). Pressure gradients from linear head accelerations have been shown to associate with focal injuries such as skull fractures, and traumatic brain injuries such as subdural hematoma (Gennarelli et al., 1971; Graham et al., 1995; Ommaya and Gennarelli, 1974).

2.5.2 Rotational Acceleration

Rotational acceleration has been proposed as more useful for predicting the risk for concussion (King et al., 2003; Kleiven, 2006; Post and Hoshizaki, 2015). Brain tissue is relatively resistant to strains created by intracranial pressures, but more vulnerable to diffuse axonal damage resulting from the strains created by shear forces (Meaney and Smith, 2011). Early research conducted by Holbourn (1943) demonstrated that the shear strains leading to axonal damage in brain injuries could not be caused by translational accelerations alone. Further studies by Gennarelli et al. (1982) were able to create a wide range of brain injuries in animal models solely through the application of rotational head accelerations. Rotational head accelerations have been found to create greater shear forces in the brain, which are more closely correlated with the brain tissue deformation characteristics found to lead to concussion (Kimpara and Iwamoto, 2012; King et al., 2003; Meaney and Smith, 2011; Post et al., 2013).

2.5.3 Maximum Principal Strain

Three-dimensional finite element (FE) modelling based on material characteristics of the brain structures have been used to predict the brain tissue response experienced during the inertial loadings of the head (Horgan and Gilchrist, 2003; Kleiven, 2002; Post et al., 2012). Brain tissue deformation metrics have been proposed as a better injury predictor for risk and severity of concussion than either linear or rotational acceleration (Kimpara and Iwamoto, 2012; King et al., 2003; Post and Hoshizaki, 2015; Zhang et al., 2004). Maximum principal strain (MPS) is a commonly used measure of brain tissue deformation in existing brain injury risk literature (Hoshizaki et al., 2013). MPS is defined by tensile strain occurring as tissues are stretched along its principle axis, and is calculated as a percentage of the tissue elongation relative to its original length (Bain and Meaney, 2000; Silva, 2006). MPS has been reported to be well-correlated with predicting the risk of brain injury (Hoshizaki et al., 2013; Post et al., 2012; Zhang et al., 2004). FE modelling has also been recently used in tandem with diffuse tensor imaging (DTI) methods to examine the relationship between levels of brain tissue strain and WM diffusivity with diagnosed concussions (McAllister et al., 2012). McAllister et al. (2012) found that maximum strain levels could be correlated with WM diffusivity measures within brain structures such as the corpus callosum. However, even without mechanical tissue damage, sub concussive levels of brain tissue strain have also been associated with the disruption of signal transmission in the nerve tissues (Bain and Meaney, 2000; Hoshizaki et al., 2013).

2.5.4 Brain Injury Risk Thresholds

Zhang et al. (2004) examined injury risk thresholds for mTBI in professional football and reported that peak linear accelerations of 66g, 82g and 106g correlated with 25%, 50% and 80% risks for suffering an mTBI respectively. Peak rotational accelerations of 4600 rad/s^2, 5900 rad/s^2 and 7900 rad/s^2 were associated with 25%, 50% and 80% mTBI risks, and brain tissue strains of 0.14, 0.19 and 0.24 were reported for 25%, 50% and 80% risks for mTBI respectively (Zhang et al., 2004). However, injury thresholds developed in professional football may not necessarily be representative of thresholds for other sporting environments. Rousseau (2014) reported that peak MPS levels of 0.30 for shoulder impacts, and 0.14 for extended elbow impacts, correlated with a 50% risk for concussion in adult professional hockey players. Other research has also suggested that children, though not adolescents, are also at a greater risk for suffering concussion from lower magnitudes of brain tissue strains when compared to adults (Dawson, 2016). While there is limited research regarding brain injury thresholds in the youth population, it remains important to consider the different sporting contexts in which existing research has been conducted.

2.5.5 Head Impact Events in Hockey

Brain trauma in hockey most commonly results from falling to the ice, collision with body segments, such as the shoulder or elbow, or contact with the boards or glass (Emery and Meeuwisse, 2006; Hutchison, 2011; Kendall et al., 2012a; Wilcox et al., 2014). Research in the National Hockey League (NHL) reported that 93.4% of concussive head impacts involved contact with a teammate/opponent, while only 6.6% of concussions involved a fall or trip (Hutchison, 2011). Of the concussions that involved body contact, 55% were from initial contact with the shoulder, 20% with the elbow, and 12% with the gloves. Additionally, 35% of all concussive events in the NHL also involved direct contact of the player’s head with the boards or the glass (Hutchison, 2011). In non-professional collegiate men’s hockey, approximately half (50.4%) of the head impact events have been reported to result from contact with another player (Wilcox et al., 2014). Wilcox et al. (2014) also found that only 7% of head impact events were to the ice, 31.1% were from contact to the boards/glass, and less than 2% involved either the stick or the puck.

While detailed analyses of head impact distributions exist within adult hockey, similar studies of this scope have not been conducted in youth. Stuart et al. (1995) reported about half of all youth hockey injuries involved collisions with another player or object, while Emery and Meeuwisse (2006) reported that 75% of injuries in youth hockey were the result of direct contact with another player. However, falls have been reported to be the leading cause of sports-related brain trauma in youth (Selassie et al., 2013; Yue et al., 2016). Children aged 6-12 are reported to be more likely to sustain head injuries from falling in comparison to adolescents (aged 13-16), who are in turn more likely to suffer head injuries from sport-related collisions (Willer et al., 2004). This is consistent with trends shown in youth hockey, as collision events from body checking has been directly associated with an increase in concussion risk among Pee Wee and Bantam-aged athletes (Emery and Meeuwisse, 2006; Emery et al., 2010a,b).

This can have important implications on how youth hockey players sustain potential head impacts and brain trauma as they progress through adolescence. While they are developing their skating abilities at younger ages, these athletes are less skilled and more susceptible to incidental head impacts from falling to the ice or into the boards during play. As they develop into bigger, more skilled athletes, the competitive environment changes as they are introduced to increased contact from body checking and are more prone to head impacts from collision-related events with other players.

2.5.6 Head Impact Characteristics

Differences in impact characteristics create head accelerations that influence brain tissue response in different regions of the brain (Guskiewicz et al., 2007b; Hoshizaki et al., 2013). Existing research has described different types of head impact events in hockey with unique biomechanical characteristics and subsequent risks for brain trauma (Kendall et al., 2012a; Kendall, 2016; Rousseau, 2014). For example, helmeted head to ice falls are markedly distinct from body collision events in terms of its dynamic response magnitudes and impact loading curves (Kendall, 2016). Dynamic impact loading curves can significantly affect brain tissue responses and are influenced by factors including the surface compliance, which differs between ice, body segments, or stationary objects such as the boards or the glass (de Grau Amezcua, 2017; Hoshizaki et al., 2013; Post et al., 2012; Post et al., 2013). The effective striking mass of different body segments may also influence head impact kinematics during collision events in hockey (Rousseau and Hoshizaki, 2015). In adult hockey players, Rousseau and Hoshizaki (2015) calculated the effective impacting mass of shoulder strikes as 14.6% (±3.6) of the athlete's body mass, while 5.4% (±1.8) of body mass was calculated for extended elbow strikes. Rousseau (2014) also analyzed real-life impact velocities of collision events resulting in both concussion and no injury in the NHL. These velocities ranged between 4.1-9.0 m/s (mean: 6.0 m/s) for concussive collisions, and between 3.2-8.6 m/s (mean: 5.8 m/s) for non-injurious collisions. While similar research remains limited in youth hockey populations, the average skating velocities for Pee Wee and Bantam hockey players have been reported to be approximately 4.9 m/s and 5.3 m/s respectively (Montgomery, 1988). These impact characteristics, along with skill levels and playing rules, all contribute towards creating competition environments with unique brain trauma risks associated with head impact events for different player ages in hockey.

CHAPTER 3: METHODOLOGY

3.1 Overview

Video footage of youth hockey games were collected as part of an ongoing youth hockey brain trauma project at the Neurotrauma Impact Science Laboratory (NISL). Pee Wee (aged 11-12 years old) and Bantam (aged 13-14 years old) hockey teams were included in the scope of this thesis project. Head impact events were logged and clipped using a video capture software. As per NISL protocol, further video analyses were used to determine the head impact event types, impact locations, and impact velocities. Exemplar impact reconstructions were conducted to represent confirmed head impact events that were reported at each event type category (Section 3.3.2), location category (Section 3.3.3), and velocity category (Section 3.3.4). Head impact kinematic data were collected from these exemplar reconstructions and input into a finite element model to determine the MPS values resulting from the head impact events.

3.2 Video Capture

In-game video footage of participating competitive youth hockey teams were collected from Ontario and Quebec leagues during the 2016-2017 regular season. A total of 16 Pee Wee and 16 Bantam hockey games were included for the purpose of this study. Video footage followed the puck during gameplay and was filmed without image zoom to allow for the maximum amount of ice surface to be recorded. Researchers were instructed to film the videos with the camera placement at centre ice and with a raised camera view overlooking the ice surface at an approximately 45º angle (Figure 1). This camera view accounted for 25/32 (78.1%) of the hockey games included in this study. Due to accessibility issues at some of the arenas, 6/32 (18.8%) of the remaining games were filmed from a raised camera angle located at the corner of the arena, and 1/32 (3.1%) was filmed from an ice-level angle located at centre ice.

Figure 1. Typical camera placement and angle for the youth hockey video footage.

Following this initial video collection, an open-access video capture software (WM Capture 8.5.3, 2016) was used to re-capture all of the obtained footage at 25 frames per second. This allowed for additional video analyses to be conducted using Kinovea software (0.8.20, 2016) as further described in Section 3.4.1.

3.3 Head Impact Event Categorization

3.3.1 Inclusion/Exclusion Criteria

Video footage of the 16 Pee Wee and 16 Bantam hockey games included in this study were each reviewed twice by two separate researchers who received training on the NISL youth hockey brain trauma protocol. Observed head impact events from the video footage were logged as either *confirmed head impacts* (CHI) or *suspected head impacts* (SHI).

The inclusion criteria for CHI were defined as having both the impact event type and the head contact itself clearly visible within the video. SHI were defined as the head contact not being clearly visible in the video, but suspected by the researcher given the sequence of play leading to the impact event. For example, the moment of head contact for SHI may have been obscured by other body segments, or may have been difficult to determine due to the quality of the video image or camera angle.

All of the head impact events logged by the initial two researchers were collated by an experienced, third researcher, and any duplicate events were removed from the final dataset. This third researcher also resolved any discrepancies (i.e. the 'tiebreaker') between the original reviewers with regards to categorizing an event as either a CHI or SHI. For the purposes of this study, only CHI events were included in subsequent Kinovea video analyses and exemplar laboratory reconstructions. However, events logged as SHI were retained and included for certain head impact frequency analyses. For some analyses, the frequency of CHI and SHI were also collated and defined as *combined head impacts* (CBDHI).

3.3.2 Impact Event Type

The head impact events were categorized within the following event types representing distinct mechanisms of head contact: 1) *Head to Ice*; 2) *Shoulder to Head*; 3) *Elbow to Head*; 4) *Head to Head*; 5) *Head to Boards*; 6) *Head to Glass*; 7) *Punch to Head*; 8) *Puck to Head*; and 9) *Other*. Events categorized as '*other*' included head contact occurring with body segments not included in the aforementioned list such as the knee, hip, or chest, and these events were excluded from the study. For the scope of this thesis, punch to head and puck to head impact events were excluded from Kinovea video analyses and exemplar laboratory reconstructions; however, any reported punch and puck events were included for head impact frequency analyses.

3.3.3 Impact Location

The head impact location categories used in this study were adapted from existing hockey-related video analysis research (Hutchison, 2011; Kendall, 2016; Rousseau, 2014). These categories included the: 1) *Front*; 2) *Front Boss*; 3) *Side*; 4) *Rear Boss*; 5) *Rear*; and 6) *Crown* locations of the head. These impact locations divided the head into eight, equal 45º regions within the transverse plane, in addition to the "crown" region located at the top of the head along the vertical axis (Figure 2a). An impact elevation grid was also used to divide the head into six equal regions within the sagittal plane (Figure 2b) to assist the researcher visually with the impact reconstructions as further described in Section 3.5.

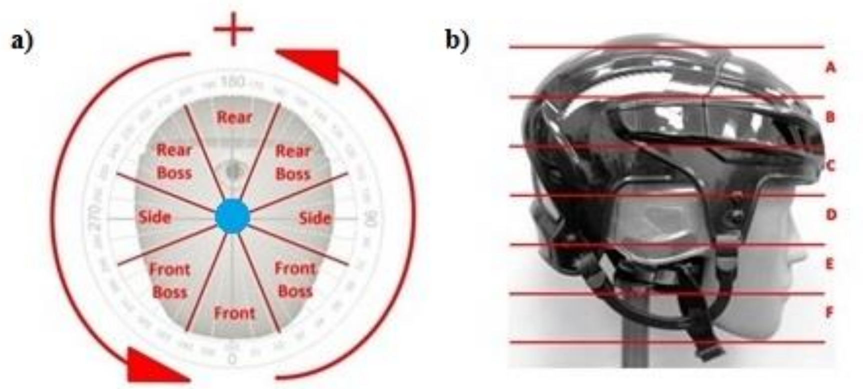


Figure 2. a) Impact location reference grid divided into eight 45° separations in the transverse plane. The "Crown" location is represented by the blue dot along the vertical axis; b) Impact elevation reference grid divided into six elevations within the sagittal plane.

3.3.4 Impact Velocity

All head impact events were grouped within the following defined impact velocity categories: *Very low* (0-1.99 m/s); *Low* (2.00-3.99 m/s); *Medium* (4.00-5.99 m/s); *High* (6.00-7.99 m/s); *Very high* (≥ 8.00 m/s).

During the initial video review, both CHI and SHI were logged by researchers as *estimated velocity* categories. Head impact velocities for CHI were subsequently determined using Kinovea video analyses and placed into *calculated velocity* categories. Velocity calculations were not conducted for the SHI and these events remained logged within their respective *estimated velocity* categories from the initial video review.

3.4 Video Analysis

3.4.1 Kinovea

Video analysis techniques have been commonly used in previous research to calculate biomechanical parameters in sport-related settings such as hockey, football, and rugby (Fréchède and McIntosh, 2009; Post et al., 2014; Rousseau, 2014). These techniques have been useful for determining important criteria for impact reconstructions including impact locations and inbound velocities. An open-access video analysis software (Kinovea 0.8.20, 2016) was used in this study to verify head impact event types and impact locations, as well as calculate the impact velocities of the impact event. The use of Kinovea software for determining skating speeds from hockey video has been recently validated against speeds calculated using high-speed cameras placed at ice-level (Post et al., 2018). Post et al. (2018) determined that there were no significant differences between using Kinovea video analysis or the high-speed camera for calculating skating speeds and this methodology was consistent with ranges of accuracy and error found in the existing literature (Fréchède and McIntosh, 2009; McIntosh et al., 2000; Newman et al., 2005).

3.4.2 Inclusion/Exclusion Criteria

Kinovea video analyses were conducted to calculate impact velocities for CHI events if the following criteria were met: a) there was a definitive head impact with clear contact to the head resulting in head motion; b) the impact event type was clear; c) there were reference markings available on the playing surface; d) the exact moment of the head impact event can be identified from the video. CHI events which did not meet this designated criteria remained categorized within their original *estimated velocities*.

A flowchart of the logged head impact events included for Kinovea velocity calculations is shown in Figure 3. 16/79 (20.3%) of the CHI events in Pee Wee (1 punch, 1 puck, 14 other), as well as 14/89 (15.7%) of the CHI events in Bantam (6 punches, 1 puck, 7 other) were excluded from video analyses and impact reconstructions. 44/63 (69.8%) of the remaining Pee Wee CHI events met the inclusion criteria for Kinovea analyses and had *calculated velocities*; 19/63 (30.2%)

did not meet the Kinovea inclusion and were categorized as *estimated velocities*. For CHI in Bantam, the velocity for 50/75 (66.7%) of the remaining events could be calculated using Kinovea, and 25/75 (33.3%) of the events could not.

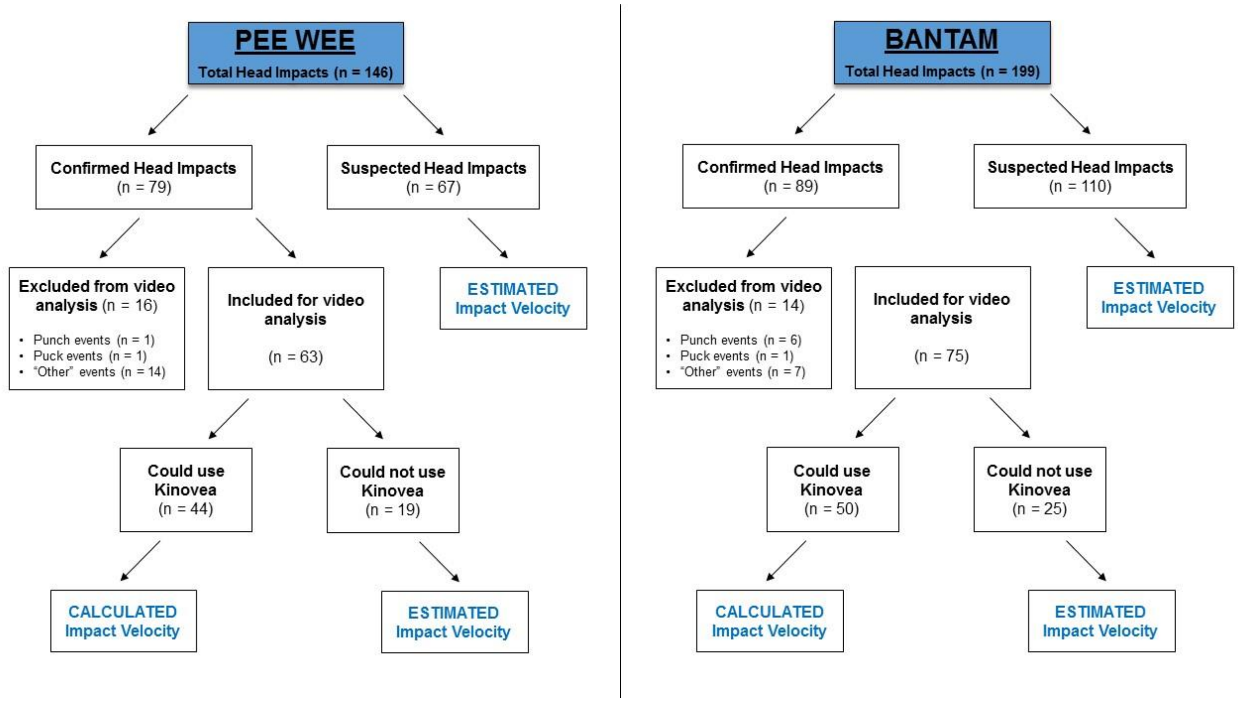


Figure 3. Flow chart depicting head impact event inclusion and exclusion for Kinovea video analyses and impact velocity calculations.

3.4.3 Velocity Calculation

To calculate the impact velocities for CHI (Figure 4), the video footage used in this study was recorded at a frame rate of 25 frames per second and the physical dimensions of the hockey rinks were obtained (Appendix A). 20/32 (62.5%) of the games included in this study were played on an NHL-sized rink. Rink dimensions for the remaining 12/32 (37.5%) arenas were measured in person by trained NISL researchers. Using Kinovea, a perspective grid calibration was applied to scale the video image to known surface dimensions on the ice, boards, glass, or net (Figure 5, Figure 6).

The impacting velocities were calculated given:

$$\text{Velocity} = \frac{\text{Distance travelled}}{\text{Time to impact}}$$

Figure 4. Formula for calculating impact velocities; where *Distance Travelled (d)* = distance between the impacted head and the "impactor" (ie: shoulder, elbow, etc.); and *Time to impact (t)* = the number of frames before the moment of impact / 25 frames per second.

For collision events (shoulder to head, elbow to head, head to head, head to boards, head to glass), the distance between the impacted head and the impactor was calculated using a horizontal perspective grid laid upon the ice surface at 5 frames prior to the moment of impact (*t = 0.2 seconds*) (Figure 5).

Figure 5. Perspective grid calibration and distance travelled shown at 5 frames prior to an elbow to head impact event.

For falling events (head to ice), the distance between the impacted head and the ice surface was calculated using a vertical perspective grid laid on the boards, glass, or net at either 1 frame (*t = 0.04 seconds*) or 2 frames (*t = 0.08 seconds*) prior to the moment of impact (Figure 6).

Figure 6. Perspective grid calibration and distance travelled shown at 1 frame prior to head to ice impact event.

Impact velocities for each of head impact events were calculated twice by the same researcher. All of the confirmed head impact events were reviewed using Kinovea once over (Trial 1), and then re-calculated for a second time within a 2-week timeframe following the initial review (Trial 2). The final *calculated velocity* for each impact event was taken as an average of two velocities determined from Trial 1 and Trial 2. If the difference in velocities calculated between Trials 1 and 2 was ≥ 1.00 m/s, a third review (Trial 3) was conducted. In these cases, the two Kinovea velocities that were closest in value were averaged and used as the final *calculated velocity* for that impact event. The calculated Kinovea velocities for each of the confirmed head impact events are reported in Appendix B.

3.5 Head Impact Reconstructions

3.5.1 Exemplar Categories

For this study, exemplar impact reconstructions were conducted for the different event types of interest, across each of the impact location categories and each of impact velocity categories as defined in Section 3.3. Exemplar events were only reconstructed within the categories where a *confirmed head impact* was reported to have occurred (Figure 7). One CHI event was excluded from reconstruction due to it resulting from a collision with a referee (medium velocity elbow event to the side location). Another CHI event was excluded due to its calculated velocity being too high to be reconstructed using the equipment in this study (high velocity elbow event to the front boss location). Therefore, a total of 71 exemplar impact reconstructions (37 Pee Wee and 34 Bantam) were conducted for this study (Table 1, Table 2).

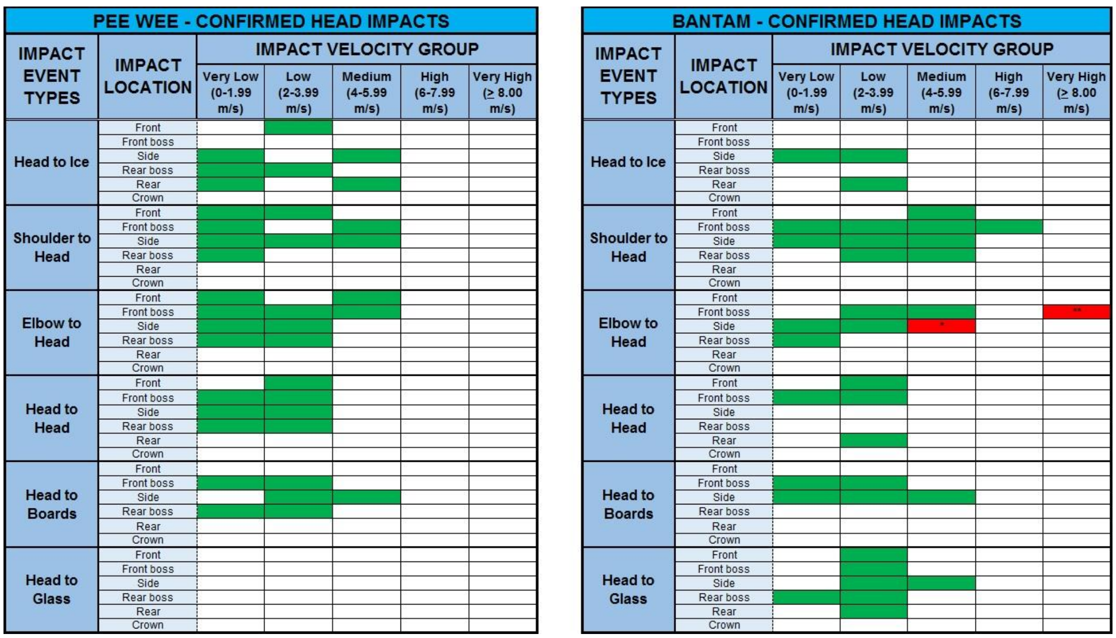


Figure 7. Each coloured cell represents an exemplar category with reported confirmed head impact(s). Red cells denote exemplar categories with events which were excluded.

To determine the inbound velocity for each exemplar impact reconstruction, the *calculated velocities* of the CHI events included within the respective exemplar category were averaged together. Any CHI which could not be analyzed using Kinovea were still incorporated within exemplar categories according to their *estimated velocities*. In the case where an exemplar category included CHI events with both *calculated* and *estimated velocities*, only the *calculated velocities* were used to determine the inbound velocity for the exemplar reconstruction. However, if an exemplar category only included CHI events with *estimated velocities*, then the median value of the respective velocity category was used for the impact reconstruction instead. Median values for each velocity category were: *Very low* (1.00 m/s); *Low* (3.00 m/s); *Medium* (5.00 m/s); *High* (7.00 m/s).

To determine the impact location used for each exemplar reconstruction, the most common point of head contact observed from CHI events within the exemplar category was selected. The criteria considered when choosing the most appropriate impact location for the reconstruction included: 1) the more common side of the head where impacts occurred (i.e., left or right); 2) the more common impact elevation where the impacts occurred (Figure 2b); and 3) the more common "hockey play" that was typically observed in that exemplar category during video review.

In the case where only one CHI was reported in an exemplar category, this event was used as the exemplar event. Clipped videos of the CHI events pertaining to each exemplar were reviewed again immediately prior to the reconstructions. Three impacts were conducted per reconstruction to obtain an average of peak dynamic response data, which were used as the inputs for finite element model (Section 3.5.5). Accelerometer data were collected at 20 KHz and processed using a TDAS Pro Lab system (DTS, Seal Beach, CA). Each impact location per helmet was only used for one exemplar reconstruction to minimize the effects of helmet material degradation on the data collection. A sample impact reconstruction report, including the Kinovea velocity calculations, is shown in Appendix C.

Table 1. Summary of event characteristics used for the exemplar head impact reconstructions in Pee Wee hockey.

	# of CHI (CV)	# of CHI (EV)	Velocity Category	Target Velocity (m/s)	Impact Location	Impact Elevation
Ice						
PW-I-1	1	0	Very low	1.19	Side – L	C
PW-I-2	2	0	Very low	1.38	Rear	C
PW-I-3	1	0	Very low	1.63	Rear Boss – L	C
PW-I-4	1	0	Low	3.00	Front	D
PW-I-5	2	1	Low	3.06	Rear Boss – R	B
PW-I-6	1	0	Medium	4.75	Side – L	C
PW-I-7	1	0	Medium	4.00	Rear	C
Shoulder						
PW-S-1	1	1	Very low	1.73	Front	C
PW-S-2	1	0	Very low	1.70	Front Boss – R	C
PW-S-3	0	2	Very low	1.00	Side – R	D
PW-S-4	2	0	Very low	0.85	Rear Boss – R	D
PW-S-5	1	0	Low	2.53	Front	D
PW-S-6	3	0	Low	2.28	Side – R	D
PW-S-7	3	0	Medium	5.28	Front Boss – R	D
PW-S-8	1	0	Medium	5.80	Side – R	D
Elbow						
PW-E-1	1	0	Very low	1.50	Front	E
PW-E-2	1	0	Very low	1.00	Front Boss – R	C
PW-E-3	1	2	Very low	1.25	Side – R	D
PW-E-4	1	0	Very low	0.80	Rear Boss – R	D
PW-E-5	1	0	Low	3.30	Front Boss – L	C
PW-E-6	3	0	Low	2.76	Side – L	D
PW-E-7	3	0	Low	2.18	Rear Boss – R	C
PW-E-8	1	0	Medium	5.15	Front	E
PW-E-9	1	0	Medium	4.40	Front Boss – R	E
Head						
PW-H-1	0	1	Very low	1.00	Front Boss – L	F
PW-H-2	2	0	Very low	1.38	Side – L	D
PW-H-3	0	1	Very low	1.00	Rear Boss – R	B
PW-H-4	1	1	Low	3.93	Front	C
PW-H-5	0	1	Low	3.00	Front Boss – L	C
PW-H-6	1	1	Low	3.93	Side	C
PW-H-7	0	1	Low	3.00	Rear Boss – R	C
Boards						
PW-B-1	1	1	Very low	1.98	Front Boss – L	C
PW-B-2	1	2	Very low	1.58	Rear Boss – L	B
PW-B-3	1	0	Low	2.33	Front Boss – L	B
PW-B-4	2	1	Low	2.73	Side – L	C
PW-B-5	1	0	Low	3.38	Rear Boss – R	C
PW-B-6	0	3	Medium	5.00	Side – L	C

CV = CHI with confirmed velocities, EV = CHI with estimated velocities;
L = left, R = right (where appropriate)

Table 2. Summary of event characteristics used for the exemplar head impact reconstructions in Bantam hockey.

	# of CHI (CV)	# of CHI (EV)	Velocity Category	Target Velocity (m/s)	Impact Location	Impact Elevation
Ice						
BN-I-1	1	0	Very low	0.38	Side – R	B
BN-I-2	1	0	Low	2.13	Side – R	D
BN-I-3	1	2	Low	3.00	Rear	C
Shoulder						
BN-S-1	2	1	Very low	1.44	Front Boss – R	D
BN-S-2	1	1	Very low	1.33	Side – L	D
BN-S-3	7	3	Low	3.23	Front Boss – L	D
BN-S-4	5	0	Low	2.85	Side – L	D
BN-S-5	0	1	Low	3.00	Rear Boss – L	E
BN-S-6	4	0	Medium	4.98	Front	D
BN-S-7	2	0	Medium	4.21	Front Boss – R	E
BN-S-8	0	1	Medium	5.00	Side – R	C
BN-S-9	1	0	Medium	5.00	Rear Boss – L	E
BN-S-10	1	0	High	6.45	Front Boss – L	E
Elbow						
BN-E-1	0	2	Very low	1.00	Side – L	C
BN-E-2	1	0	Very low	1.75	Rear Boss – L	C
BN-E-3	1	1	Low	2.30	Front Boss – L	D
BN-E-4	3	1	Low	2.75	Side – R	D
BN-E-5	3	0	Medium	4.53	Front Boss – R	D
BN-E-6	1	0	Medium	9.08	Front Boss – L	D
Head						
BN-H-1	4	0	Very low	1.69	Front Boss – R	E
BN-H-2	1	0	Low	2.19	Front	D
BN-H-3	4	0	Low	3.25	Front Boss – L	D
BN-H-4	1	0	Low	2.19	Rear	B
Boards						
BN-B-1	2	0	Very low	1.38	Front Boss – L	D
BN-B-2	2	0	Very low	1.28	Side – R	D
BN-B-3	0	2	Low	3.00	Front Boss – L	C
BN-B-4	2	0	Low	2.98	Side – R	C
BN-B-5	1	0	Medium	4.58	Side – L	C
Glass						
BN-G-1	1	0	Very low	1.30	Rear Boss – L	B
BN-G-2	0	1	Low	3.00	Front	C
BN-G-3	0	2	Low	3.00	Front Boss – R	D
BN-G-4	0	1	Low	3.00	Side – R	C
BN-G-5	2	0	Low	3.36	Rear Boss – R	C
BN-G-6	0	1	Low	3.00	Rear	C
BN-G-7	1	0	Medium	4.35	Side – L	D

CV = CHI with confirmed velocities, EV = CHI with estimated velocities;
L = left, R = right (where appropriate)

3.5.2 5th Hybrid III Headform and Neckform

A 5th Hybrid III headform was used for all of the exemplar head impact reconstructions based on its correlation with the average head mass and circumference of male adolescent youths (Nellhaus, 1968; Nguyen et al., 2012). The Hybrid III headform was attached to an unbiased 5th Hybrid III neckform and instrumented with a 3-2-2-2 accelerometer array to collect the three-dimensional head impact dynamic response data (Padgaonkar et al., 1975). This Hybrid III headform was outfitted with a certified CCM Tacks 110 helmet and a certified FM580 cage for all of the impact reconstructions conducted in this study.

3.5.3 Head to Ice, Boards, and Glass Impact Events

A Cadex monorail drop rig was used to reconstruct the exemplar head to ice, head to boards, and head to glass impact events. The 5th Hybrid III headform and neckform was secured to a monorail drop carriage and attached to a guided 4.7m monorail via two linear ball bushings. This drop carriage was released using a pneumatic piston to drop the headform system onto an anvil consisting of the appropriate impacting surface at the targeted velocities.

A metal anvil filled with water that was frozen for ≥ 24 hours at -25°C was used for the head to ice impact reconstructions (Figure 8a). Two of these ice anvils were used alternatingly per impact reconstruction to minimize melting of the ice during the testing protocol. An anvil affixed with a cut-out section of high density polyethylene hockey boards was used for the head to boards impact reconstructions. Depending on the impact event observed during the video review, the surface of the anvil for boards was fastened at either a 90° or 45° angle relative to the direction of the carriage drop (Figure 8b). Lastly, the head to glass impact reconstructions were conducted with a panel of acrylic glass (Plexiglas). This Plexiglas panel was secured via a wooden frame and placed at a 90° angle relative to the drop carriage at the bottom of the Cadex monorail (Figure 8c).

a)  b)  c) 

Figure 8. a) Head to ice impact reconstruction with frozen ice anvil; b) Head to boards impact reconstruction with polyethylene anvil at a 90° [left] and 45° [right] angle; c) Head to glass impact reconstruction with acrylic Plexiglas panel.

3.5.4 Shoulder to Head, Elbow to Head, and Head to Head Impact Events

A swinging pendulum impactor system was used to reconstruct the shoulder to head, elbow to head, and head to head impact events. The 5th Hybrid III headform was secured via an adjustable 360° base and attached to a low-friction sliding table located at the end of the pendulum striker. This sliding table was rotated, raised, or lowered according to the impact location and elevation of the head impact event. The pendulum striker was fastened via a metal clasp to a fixed, motorized wire spool which raised the striker to a pre-determined height (Figure 9a). The striker was then manually released from the metal clasp to impact the headform system at the desired velocities. Targeted impacting locations and velocities were verified following every impact with the use of a high-speed camera (Figure 9b).

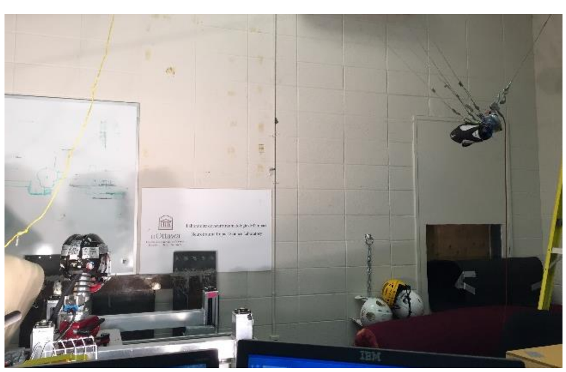
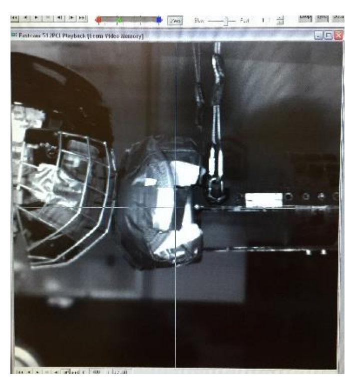
a)  b) 

Figure 9. a) Impact reconstruction set-up depicting the elbow striker attached and raised via a motorized wire spool; b) High-speed camera depicting the shoulder striker at the frame of impact.

For the shoulder to head impact reconstructions, a Reebok 11k hockey shoulder pad and vinyl-nitrile (VN) foam cap and was attached to a hollow, metal striking frame with an adjustable mass (Rousseau, 2014) (Figure 10a). The combined mass of the shoulder pad, VN foam, and metal frame was 3.76 kg. The effective striking mass of the shoulder impacts were calculated using approximately 14.6% of the average weight for Pee Wee (49.05 kg) and Bantam-aged (61.55 kg) children (Fryar, 2012; Rousseau, 2014). Additional weights were added to the metal frame to reach striking masses of 7.20 kg and 9.00 kg for the Pee Wee and Bantam shoulder reconstructions respectively.

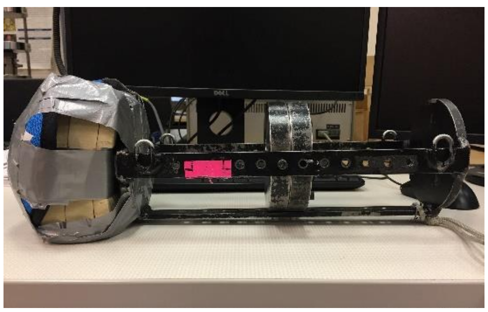
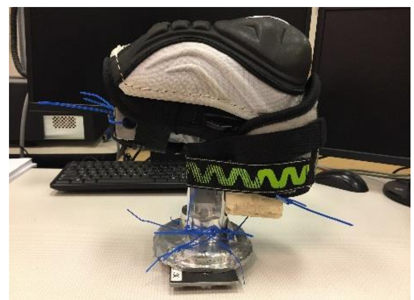
a)  **b)** 

Figure 10. a) Shoulder to head striker; b) Elbow to head striker.

A customized elbow striker weighing 2.80 kg was used to reconstruct the head to elbow impact events. This striker consisted of a metal frame equipped with a Reebok 11k hockey elbow pad and VN foam cap (Rousseau, 2014) (Figure 10b). Effective striking mass of elbow impacts were calculated as approximately 5.4% of the average weight for Pee Wee and Bantam-aged children (Fryar, 2012; Rousseau, 2014). For the Bantam elbow reconstructions, weights were attached to the metal frame to increase the striking mass to 3.30 kg. No additional weights were added to the elbow striker for the Pee Wee reconstructions.

Lastly, a medium NOCSAE headform equipped with a CCM Tacks 110 helmet and FM580 cage (total mass = 4.00 kg) was used as the striker for the head to head impact reconstructions.

This headform striker was attached to the pendulum impactor system and released following the same protocol as the shoulder and elbow impact reconstructions (Figure 11).

Figure 11. Head to head NOCSAE striker attached to the swinging pendulum impactor system.

3.5.5 Finite Element Model

The University College Dublin Brain Trauma Model (UCDBTM) was the three-dimensional finite element model used to determine maximum principal strains (MPS) from the head impact reconstructions (Figure 12). Based on existing data from MRI studies and previous research conducted in the adolescent population, a 95% scaled model of the adult UCDBTM was used to measure MPS from the head impacts included in this study (Dawson, 2016; Mennes et al., 2014; Post et al., 2017). The geometry of the UCDBTM was developed using CT and MRI scans of an adult male cadaver (Horgan and Gilchrist, 2003; 2004). The UCDBTM is made up of 26,000 hexahedral elements consisting of the scalp, skull, pia, falx, tentorium, cerebrospinal fluid, grey and white matter, cerebellum, and brainstem (Horgan and Gilchrist, 2003; 2004). Material properties and brain tissue characteristics for the UCDBTM are shown in Table 3 and Table 4 respectively.

Table 3. Material properties of the University College Dublin Brain Trauma Model.

Material	**Young's Modulus (MPa)**	**Poisson's Ratio**	**Density (kg/m^3)**
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	15000	0.5	1000
Grey Matter	Hyperelastic	0.49	1060
White Matter	Hyperelastic	0.49	1060

Table 4. Material characteristics of the brain tissue for the University College Dublin Brain Trauma Model.

Material	**Shear modulus (kPa)**		**Decay Constant (GPa)**	**Bulk Modulus (s^{-1})**
	G_0	**G_∞**		
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

Behaviour of the brain tissue material was modelled using a linear viscoelastic model in combination with a large-deformation theory (Horgan and Gilchrist, 2003). Brain tissue was defined as viscoelastic in shear, and the compressive behaviour of the brain was considered as elastic. The shear characteristics of the viscoelastic brain was represented by the equation:

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

where G_∞ is the long shear modulus, G_0 is the short term shear modulus, and β is the decay factor. Brain shear was modelled with a hyperelastic material in combination with the viscoelastic material property. This hyperelastic model was represented by the equation:

$$C_{10}(t) = 0.9C_{01}(t) = 620.5 + 1930e^{-t/0.008} + 1103e^{-t/0.15} \text{ (Pa)}$$

where C_{10} and C_{01} are temperature-dependent material parameters and t is the time in seconds (Horgan and Gilchrist, 2003). Use of the UCDBTM model has been validated in cadaveric research and for use in real-world brain injury reconstructions (Hardy et al., 2001; Doorly and Gilchrist, 2006; Nahum et al., 1977).

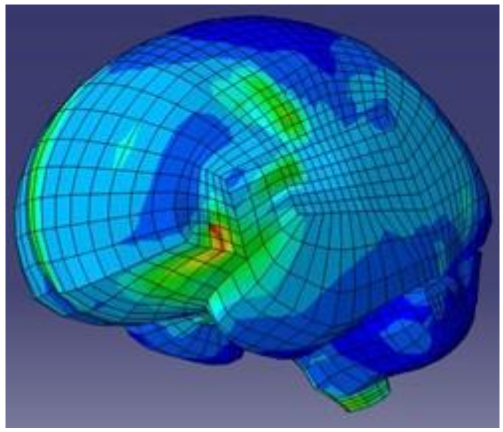


Figure 12. University of College Dublin Brain Trauma Model depicting gradients of low to high brain tissue strain in different regions of the brain.

MPS values calculated from the head impact events in the current study were subsequently categorized across five levels of MPS magnitudes for the frequency analyses. These MPS categories were: *Very Low* (< 8.0%); *Low* (8.0-16.9%); *Medium* (17-25.9%); *High* (26-34.9%); and *Very High* (> 35%). For the frequency analyses, the MPS value calculated from each of the exemplar impact reconstructions was counted once for every CHI event that was represented within the respective exemplar category.

3.6 Statistical Analyses

3.6.1 Reliability

Intra-rater test-retest reliability was conducted using a sample of six youth hockey games administrated at approximately two weeks between the first and second tests. A two-way mixed, intraclass correlation coefficient (ICC) was used to calculate the intra-rater reliability, with an ICC between 0.75-0.90 indicating a ‘good’ agreement and ≥ 0.90 indicating an ‘excellent’ agreement

(Koo and Li, 2016). The intra-rater reliability for the identification of the head impact events was determined to be ‘excellent’ (ICC = .957) for this study.

3.6.2 Magnitudes

Data were presented as means and standard deviations. Statistical analyses were conducted using SPSS 21 (IBM Inc., Armonk, NY, USA) with α levels set at $p < 0.05$ for significance. Shapiro-Wilk normality tests determined that the linear acceleration, rotational acceleration, and MPS magnitude data were not normally distributed. Therefore, three Mann-Whitney *U* tests were conducted to compare the magnitudes of peak linear acceleration, peak rotational acceleration, and peak MPS from head impact events between Pee Wee and Bantam-level hockey. Peak linear acceleration magnitudes collected from the exemplar impact event reconstructions within each age group were collapsed together for comparison. Magnitudes of peak rotational acceleration, and magnitudes of peak MPS from the exemplar reconstructions were also collapsed in this manner to compare between Pee Wee and Bantam hockey.

3.6.2 Frequency

The frequency of confirmed and suspected head impacts was initially logged and categorized per game. However, the lengths of the video recorded were not consistent between each of the hockey games included in this study. Frequency data were reported in terms of the number of head impacts standardized to per 1000 player-hours. An independent samples t-test was used to compare the mean frequency of head impacts per 1000 player-hours between Pee Wee and Bantam hockey. Independent samples t-tests were also conducted to compare the mean head impact frequencies per 1000 player-hours by impact event types.

Chi-squared (X^2) tests were conducted on the distribution of both CHI and CBDHI across the different impact event types to assess whether there were statistically significant associations between the age of play and type of head impact event. To determine whether the age of play is also associated with the frequency of MPS magnitudes, a third chi-squared test was used to assess the distribution of MPS magnitudes from CHI events across each of the MPS categories as described in Section 3.5.5. Cramer's V (φ_c) was used to describe the strength of association, with $\varphi_c \geq 0.3$ and $\varphi_c \geq 0.5$ indicating 'moderate' and 'strong' associations respectively (Cohen, 1988).

CHAPTER 4: RESULTS

4.1 Impact Reconstructions

Peak linear accelerations, peak rotational accelerations, and MPS values from the exemplar head impact reconstructions are reported in Table 5 and Table 6.

4.1.1 Pee Wee Exemplars

A total of 7 head to ice, 8 shoulder to head, 9 elbow to head, 7 head to head, and 6 head to boards exemplar impact events were reconstructed for Pee Wee hockey (Table 5). Three of the head to head events (PW-H-1, PW-H-2, PW-H-3) recorded impact forces below 2 g, which did not trigger the headform accelerometers. These three head to head exemplars were excluded from the dynamic response and MPS magnitude analyses. However, it could be reasonably inferred that these three exemplars would have MPS magnitudes <8.0%, given the MPS response elicited from a similar impact reconstruction (BN-H-1, MPS = 0.07; Table 6). Therefore, head impact events related to the exemplars PW-H-1, PW-H-2, and PW-H-3 were assigned to the '*very low*' MPS category for the frequency analyses as further described in Section 4.3.

4.1.2 Bantam Exemplars

For Bantam hockey, a total of 3 head to ice, 10 shoulder to head, 5 elbow to head, 4 head to head, 5 head to boards, and 7 head to glass impact events were reconstructed (Table 6). The exemplar event BN-E-6 had a calculated velocity of 9.08 m/s, which could not be reconstructed due to limitations with the pendulum impacting system. However, this head impact event was highly unusual and resulted from an illegal 'charging' infraction, and previous reconstructions of collision events at similar velocities in adult hockey has been reported to be well within the range of concussion values (Rousseau, 2014). An elbow to head impact at this calculated velocity was statistically identified to be an outlier within the context of the current study (Figure 13). Therefore, the exemplar event BN-E-6 was excluded from further data analyses.

Table 5. Peak linear acceleration, peak rotational acceleration, and maximum principal strain values from the Pee Wee head impact exemplar reconstructions.

	Velocity Category	Impact Velocity (m/s)	Impact Location	Linear Acceleration (g)	Rotational Acceleration (rad/s^2)	MPS
Ice						
PW-I-1	Very low	1.19	Side	55.0	6138.4	0.34
PW-I-2	Very low	1.38	Rear	42.3	1575.6	0.11
PW-I-3	Very low	1.63	Rear Boss	29.4	2419.0	0.17
PW-I-4	Low	3.00	Front	38.2	3089.5	0.22
PW-I-5	Low	3.06	Rear Boss	54.5	3433.9	0.22
PW-I-6	Medium	4.75	Side	131.4	11945.8	0.56
PW-I-7	Medium	4.00	Rear	87.4	3124.9	0.25
Shoulder						
PW-S-1	Very low	1.73	Front	8.6	662.1	0.06
PW-S-2	Very low	1.70	Front Boss	10.4	972.9	0.09
PW-S-3	Very low	1.00	Side	7.5	559.1	0.06
PW-S-4	Very low	0.85	Rear Boss	6.5	795.9	0.06
PW-S-5	Low	2.53	Front	12.0	1267.7	0.13
PW-S-6	Low	2.28	Side	10.7	1094.6	0.10
PW-S-7	Medium	5.28	Front Boss	21.1	3285.7	0.28
PW-S-8	Medium	5.80	Side	24.8	3538.4	0.30
Elbow						
PW-E-1	Very low	1.50	Front	4.9	482.9	0.05
PW-E-2	Very low	1.00	Front Boss	2.5	263.8	0.03
PW-E-3	Very low	1.25	Side	2.4	333.5	0.03
PW-E-4	Very low	0.80	Rear Boss	2.9	407.3	0.04
PW-E-5	Low	3.30	Front Boss	12.2	1262.7	0.12
PW-E-6	Low	2.76	Side	10.0	1403.0	0.09
PW-E-7	Low	2.18	Rear Boss	7.3	1159.4	0.08
PW-E-8	Medium	5.15	Front	17.9	1552.6	0.12
PW-E-9	Medium	4.40	Front Boss	12.3	1363.8	0.15
Head						
PW-H-1 *	Very low	1.00	Front Boss	N/A	N/A	< 0.08
PW-H-2 *	Very low	1.38	Side	N/A	N/A	< 0.08
PW-H-3 *	Very low	1.00	Rear Boss	N/A	N/A	< 0.08
PW-H-4	Low	3.93	Front	17.1	3767.8	0.21
PW-H-5	Low	3.00	Front Boss	17.6	2658.3	0.14
PW-H-6	Low	3.93	Side	15.9	1395.6	0.13
PW-H-7	Low	3.00	Rear Boss	10.9	1314.5	0.08
Boards						
PW-B-1	Very low	1.98	Front Boss	29.7	2686.6	0.26
PW-B-2	Very low	1.58	Rear Boss	18.2	1625.4	0.14
PW-B-3	Low	2.33	Front Boss	30.6	2940.6	0.27
PW-B-4	Low	2.73	Side	50.0	3606.0	0.29
PW-B-5	Low	3.38	Rear Boss	51.3	3396.2	0.24
PW-B-6	Medium	5.00	Side	147.4	10140.6	0.54

** denotes exemplar events with impact forces too low to trigger the headform accelerometers*

Table 6. Peak linear acceleration, peak rotational acceleration, and maximum principal strain values from the Bantam head impact exemplar reconstructions.

	Velocity Category	Impact Velocity (m/s)	Impact Location	Linear Acceleration (g)	Rotational Acceleration (rad/s^2)	MPS
Ice						
BN-I-1	Very low	0.38	Side	12.4	1330.5	0.10
BN-I-2	Low	2.13	Side	55.8	4947.4	0.31
BN-I-3	Low	3.00	Rear	68.8	2476.3	0.16
Shoulder						
BN-S-1	Very low	1.44	Front Boss	7.4	964.3	0.08
BN-S-2	Very low	1.33	Side	4.2	587.9	0.07
BN-S-3	Low	3.23	Front Boss	14.1	2384.3	0.20
BN-S-4	Low	2.85	Side	13.9	1353.1	0.15
BN-S-5	Low	3.00	Rear Boss	11.2	1170.9	0.11
BN-S-6	Medium	4.98	Front	21.2	2904.4	0.24
BN-S-7	Medium	4.21	Front Boss	16.1	3067.3	0.23
BN-S-8	Medium	5.00	Side	24.7	2753.4	0.26
BN-S-9	Medium	5.00	Rear Boss	22.7	2045.0	0.16
BN-S-10	High	6.45	Front Boss	13.7	3095.7	0.19
Elbow						
BN-E-1	Very low	1.00	Side	2.9	422.8	0.04
BN-E-2	Very low	1.75	Rear Boss	6.1	492.5	0.05
BN-E-3	Low	2.30	Front Boss	7.0	561.7	0.05
BN-E-4	Low	2.75	Side	7.8	1057.2	0.08
BN-E-5	Medium	4.53	Front Boss	17.3	1066.7	0.09
BN-E-6 **	Very High	9.08	Front Boss	N/A	N/A	N/A
Head						
BN-H-1	Very low	1.69	Front Boss	6.3	1128.7	0.07
BN-H-2	Low	2.19	Front	11.8	2953.1	0.19
BN-H-3	Low	3.25	Front Boss	14.0	1986.5	0.13
BN-H-4	Low	2.19	Rear	8.4	2048.9	0.12
Boards						
BN-B-1	Very low	1.38	Front Boss	19.0	2167.6	0.16
BN-B-2	Very low	1.28	Side	32.4	2311.3	0.15
BN-B-3	Low	3.00	Front Boss	32.9	3576.7	0.31
BN-B-4	Low	2.98	Side	57.3	4519.8	0.27
BN-B-5	Medium	4.58	Side	115.2	8134.8	0.49
Glass						
BN-G-1	Very low	1.30	Rear Boss	13.2	2581.0	0.14
BN-G-2	Low	3.00	Front	16.0	3895.6	0.19
BN-G-3	Low	3.00	Front Boss	15.7	2866.5	0.16
BN-G-4	Low	3.00	Side	24.3	1682.9	0.11
BN-G-5	Low	3.36	Rear Boss	27.7	5326.6	0.31
BN-G-6	Low	3.00	Rear	26.6	6379.5	0.39
BN-G-7	Medium	4.35	Side	49.6	4316.4	0.25

** denotes exemplar event which could not be reconstructed due to equipment limitations*

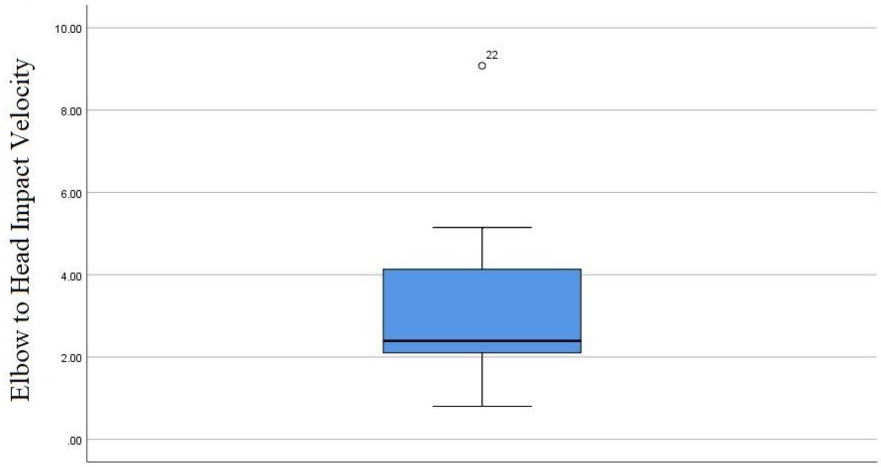


Figure 13. Boxplot depicting interquartile range of calculated elbow to head impact velocities and excluded outlier (BN-E-6).

4.2 Impact Magnitudes

The overall peak linear acceleration, peak rotational acceleration, and MPS magnitudes averaged across all of the reconstructed head impact events for Pee Wee and Bantam hockey are reported in Table 7. A total of 34 Pee Wee exemplar reconstructions were compared to 34 Bantam exemplar reconstructions for this analysis. These magnitude values collected from each impact reconstruction did not receive additional weighting based on the number of CHI represented by the exemplar event.

4.2.1 Peak Linear and Rotational Acceleration

Mean peak linear accelerations from the head impact exemplars events were 29.4 (33.9) g for Pee Wee, and 23.5 (22.7) g for Bantam. Mean peak rotational accelerations from the head impact exemplar events were 2519.5 (2540.6) rad/s^2 for Pee Wee, and 2604.6 (1760.1) rad/s^2 for Bantam. Mann-Whitney *U* tests found no significant differences when comparing the magnitudes of peak linear acceleration ($U = 589.5$, $p = 0.89$) or the magnitudes of peak rotational acceleration ($U = 514.0$; $p = 0.43$) between Pee Wee and Bantam hockey.

4.2.2 Maximum Principal Strain

The mean magnitude of MPS values from the head impact exemplar events was 0.18 (0.13) in Pee Wee and 0.18 (0.10) in Bantam. The Mann-Whitney *U* test found no significant difference in the overall MPS magnitudes between Pee Wee and Bantam hockey ($U = 532.0$; $p = 0.57$).

Table 7. Mean peak linear acceleration, rotational acceleration, and MPS from head impact events, by age group.

	Pee Wee Mean (SD)	**Bantam** Mean (SD)	***p-value***
Linear Acceleration (g)	29.4 (33.9)	23.5 (22.7)	0.89
Rotational Acceleration (rad/s^2)	2519.5 (2540.6)	2604.6 (1760.1)	0.43
MPS	0.18 (0.13)	0.18 (0.10)	0.57

4.3 Impact Frequency

4.1.1 Confirmed, Suspected, and Combined Impacts

526.85 minutes and 691.08 minutes of on-ice gameplay were reviewed across 16 games of Pee Wee and Bantam hockey respectively (Table 8). In these games, a total of 79 CHI and 67 SHI were logged for Pee Wee (PW), and a total of 89 CHI and 110 SHI events were logged for Bantam (BN) hockey. The frequency of CHI events was 17.54 per 1000 player-hours in Pee Wee, and 15.06 per 1000 player-hours of gameplay in Bantam hockey. For SHI events, the frequency was 14.87 SHI/1000 player-hours in Pee Wee, and 18.62 SHI/1000 player-hours in Bantam. When combining the CHI and SHI events together, a total of 146 CBDHI and 199 CBDHI events were reported for Pee Wee and Bantam respectively. The frequency of CBDHI events per 1000 player-hours was 32.41 CBDHI for Pee Wee, and 33.68 CBDHI for Bantam. When comparing the average frequencies of head impact events per 1000 player-hours *per analysis*, there were no significant differences found between Pee Wee and Bantam hockey for the CHI ($p = 0.56$), SHI ($p = 0.22$), or CBDHI ($p = 0.83$) events.

Table 8. Reported frequencies of confirmed (CHI), suspected (SHI), and combined (CBDHI) head impact events in Pee Wee and Bantam hockey.

	Pee Wee	**Bantam**	***p-value***
Games reviewed, n	16	16	-
Total game time, mins	526.85	691.08	-
CHI, total n	79	89	-
CHI, per 1000 player-hours	17.54	15.06	0.56
SHI, total n	67	110	-
SHI, per 1000 player-hours	14.87	18.62	0.22
CBDHI, total n	146	199	-
CBDHI, per 1000 player-hours	32.41	33.68	0.83

4.1.2 Impact Event Types

The frequency of confirmed, suspected, and combined confirmed/suspected head impact events are reported by the type of impact event in Table 9.

Table 9. Observed frequencies of confirmed, suspected, and combined head impact events in 16 games of Pee Wee and Bantam hockey, by impact event type.

	Pee Wee			**Bantam**		
	Confirmed	Suspected	Combined	Confirmed	Suspected	Combined
Head to ice	10	12	22	5	6	11
Shoulder to head	15	8	23	30	17	47
Elbow to head	15	8	23	14	11	25
Head to head	10	2	12	8	8	16
Head to boards	13	25	38	9	23	32
Head to glass	0	3	3	9	28	37
Punch to head	1	2	3	6	7	13
Puck to head	1	2	3	1	1	2

For both Pee Wee and Bantam hockey, the two most frequent types of CHI events involved shoulder to head and the elbow to head. When a confirmed head to ice impact was reported, two-thirds (10/15) of these events occurred at the Pee Wee level. However, two-thirds (30/45) of all confirmed shoulder to head events were found in Bantam hockey. 59.1% (13/22) of the CHI events to the boards occurred in Pee Wee while in contrast, 100% of the confirmed head to glass events were reported in Bantam. Interestingly, only 3 SHI and 0 CHI events to the glass were logged in Pee Wee. The overall proportions of confirmed head to elbow, and head to head impact events reported in this study were relatively consistent between Pee Wee and Bantam hockey (Figure 14).

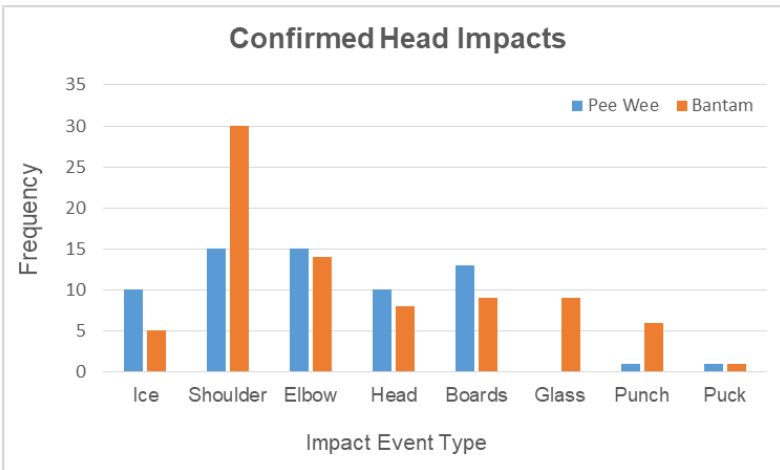


Figure 14. Confirmed head impact frequencies by impact event types for Pee Wee and Bantam.

The most frequent type of SHI events were head to boards and head to glass for Pee Wee and Bantam respectively (Table 9). When the confirmed and suspected head impact events were combined, the most frequent type of events reported were head to boards for Pee Wee, and shoulder to head for Bantam (Figure 15). The total number of CBDHI events involving the boards were similar between Pee Wee (n = 38) and Bantam (n = 32). However, there were more than twice the number of CBDHI shoulder events reported in Bantam (n = 47) than in Pee Wee (n = 23). The total frequency of CBDHI board events in Pee Wee was also similar to the frequency of CBDHI glass events in Bantam. However, there were considerably more CBDHI glass events additionally reported in Bantam (n = 37) than in Pee Wee (n = 3).

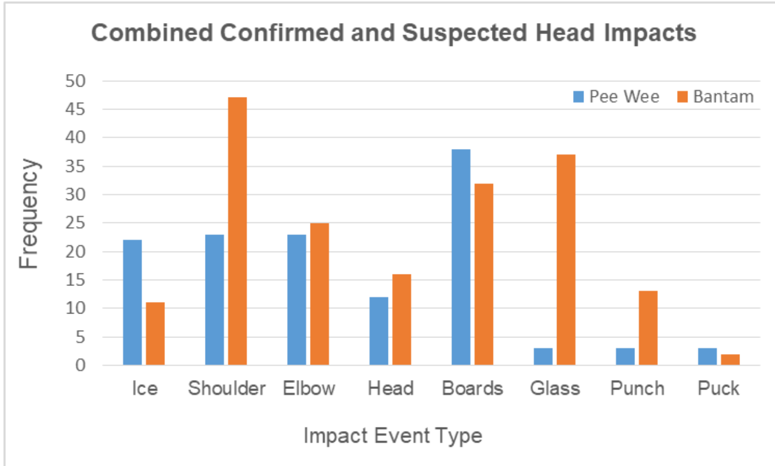


Figure 15. Combined confirmed and suspected head impact frequencies by impact event types for Pee Wee and Bantam.

A chi-squared test was conducted between the age group and the type of impact event. Punch and puck impact events were collapsed to meet assumptions for expected counts. For CHI, there was a statistically significant association found between age group and impact event types, X^2 (6) = 17.699, p = 0.006. Post-hoc analysis demonstrated that the association between these two variables was moderate (Cohen, 1988), φ_c = .347. For CBDHI, similar associations were found between age group and impact event types as well. When combining the reported frequencies of CHI and SHI, there was a statistically significant, moderate association between the age group and the type of impact event, X^2 (6) = 36.910, p < 0.001, φ_c = .345. Contingency tables for the CHI and CBDHI chi-squared tests are shown in Table 10 and Table 11 respectively.

Table 10. Cross tabulation of age group and type of head impact event (CHI).

	Impact Event Type						
	Ice	Shoulder	Elbow	Head	Boards	Glass	Punch/ Puck
Pee Wee							
Observed Count	10	15	15	10	13	0	2
Expected Count	6.6	19.9	12.8	8.0	9.7	4.0	4.0
% within Age Group	15.4%	23.1%	23.1%	15.4%	20.0%	0.0%	3.1%
% within Event Type	66.7%	33.3%	51.7%	55.6%	59.1%	0.0%	22.2%
% of Total	6.8%	10.2%	10.2%	6.8%	8.8%	0.0%	1.4%
Std. Residual	1.3	-1.1	0.6	0.7	1.0	-2.0	-1.0
Bantam							
Observed Count	5	30	14	8	9	9	7
Expected Count	8.4	25.1	16.2	10	12.3	5.0	5.0
% within Age Group	6.1%	36.6%	17.1%	9.8%	11.0%	11.0%	8.5%
% within Event Type	33.3%	66.7%	48.3%	44.4%	40.9%	100%	77.8%
% of Total	3.4%	20.4%	9.5%	5.4%	6.1%	6.1%	4.8%
Std. Residual	-1.2	1.0	-0.5	-0.6	-0.9	1.8	0.9

** 2 cells have expected counts less than 5. The minimum expected count is 3.98.*

Table 11. Cross tabulation of age group and type of head impact event (CBDHI).

	Impact Event Type						
	Ice	Shoulder	Elbow	Head	Boards	Glass	Punch/ Puck
Pee Wee							
Observed Count	22	23	23	12	38	3	6
Expected Count	13.5	28.7	19.7	11.5	28.7	16.4	8.6
% within Age Group	17.3%	18.1%	18.1%	9.4%	29.9%	2.4%	4.7%
% within Event Type	66.7%	32.9%	47.9%	42.9%	54.3%	7.5%	28.6%
% of Total	7.1%	7.4%	7.4%	3.9%	12.3%	1.0%	1.9%
Std. Residual	2.3	-1.1	0.8	0.2	1.7	-3.3	-0.9

Bantam							
Observed Count	11	47	25	16	32	37	15
Expected Count	19.5	41.3	28.3	16.5	41.3	23.6	12.4
% within Age Group	6.0%	25.7%	13.7%	8.7%	17.5%	20.2%	8.2%
% within Event Type	33.3%	67.1%	52.1%	57.1%	45.7%	92.5%	71.4%
% of Total	3.5%	15.2%	8.1%	5.2%	10.3%	11.9%	4.8%
Std. Residual	-1.9	0.9	-0.6	-0.1	-1.5	2.8	0.7

** 2 cells have expected counts less than 5. The minimum expected count is 3.98.*

The frequency of head impact event types per 1000 player-hours are reported in Table 12. In Bantam, there was a significantly greater frequency of both confirmed ($p < 0.01$) and suspected ($p < 0.001$) head to glass events per 1000 player-hours *per analysis* in comparison to Pee Wee. No other significant differences were found between Pee Wee and Bantam hockey in the frequencies of CHI or SHI *per analysis* for any of the remaining event types. However, when comparing the differences between Pee Wee and Bantam for frequencies of combined confirmed/suspected head impact events (CBDHI) per 1000 player-hours *per analysis*, there was a significantly greater frequency of head to ice impact events in Pee Wee than Bantam ($p < 0.05$). Bantam also had significantly greater frequencies of CBDHI glass events ($p < 0.001$), and CBDHI punch events ($p < 0.05$) per 1000 player-hours *per analysis* than Pee Wee hockey.

Table 12. Frequency of confirmed, suspected, and combined confirmed/suspected head impacts per 1000 player-hours for Pee Wee and Bantam hockey, by impact event type.

	Pee Wee *(per 1000 player-hours)*	**Bantam** *(per 1000 player-hours)*	***p-value*** *(per analysis)*
Confirmed			
Head to ice	2.22	0.85	0.15
Shoulder to head	3.33	5.08	0.15
Elbow to head	3.33	2.37	0.37
Head to head	2.22	1.35	0.40
Head to boards	2.89	1.52	0.21
Head to glass	0.00	1.52	< 0.01 **
Punch to head	0.22	1.02	0.15
Puck to head	0.22	0.17	0.79
Suspected			
Head to ice	2.66	1.02	0.07
Shoulder to head	1.78	2.88	0.38
Elbow to head	1.78	4.23	0.97
Head to head	0.44	2.71	0.21
Head to boards	5.55	5.42	0.24
Head to glass	0.67	6.26	< 0.001 **
Punch to head	0.44	2.20	0.13
Puck to head	0.44	0.34	0.46
Combined			
Head to ice	4.88	1.86	0.03 *
Shoulder to head	5.11	7.95	0.10
Elbow to head	5.11	4.23	0.51
Head to head	2.66	2.71	0.73
Head to boards	8.44	5.42	0.10
Head to glass	0.66	6.26	< 0.001 **
Punch to head	0.66	2.20	0.02 *
Puck to head	0.66	0.34	0.51

** denotes significance at (p<0.05); ** denotes significance at (p<0.01)*

4.5.2 Maximum Principal Strain Magnitudes

The overall frequencies of MPS magnitudes resulting from CHI events are reported by strain level categories in Table 13. In Pee Wee hockey, MPS magnitudes were most frequently observed in the *Very Low* (n = 17) and *Low* (n = 23) strain categories. In Bantam hockey, the most frequent MPS magnitudes were within the *Low* (n = 28) and *Medium* (n = 20) strain categories (Figure 16). There was a slightly higher frequency of CHI events with *High* and *Very High* MPS magnitudes reported in Pee Wee when compared to Bantam hockey.

Table 13. Frequency of maximum principal strain magnitudes from confirmed head impacts in Pee Wee and Bantam, total.

	Very Low < 8.0%	**Low** 8.0 – 16.9%	**Medium** 17 – 25.9%	**High** 26 – 34.9%	**Very High** > 35%
Pee Wee	17	23	10	9	4
Bantam	15	28	20	8	2

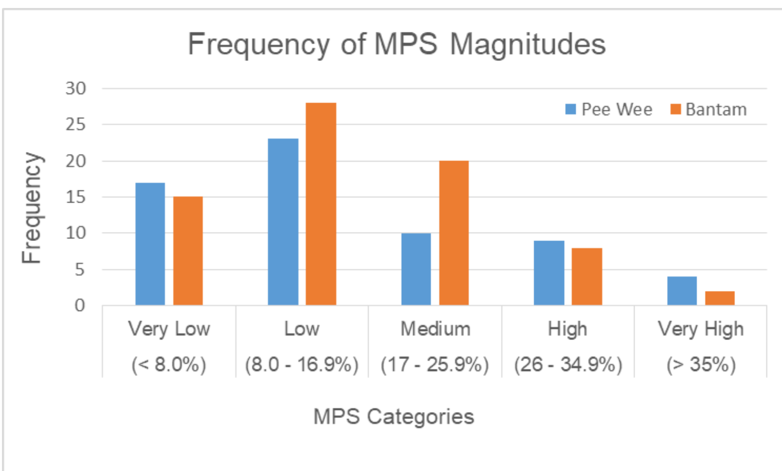


Figure 16. Frequency of MPS magnitudes reported by category in Pee Wee and Bantam hockey.

A chi-squared test was conducted to test the relationship between age group and the MPS categories. However, there was no statistically significant association found between the age group and categories of MPS, (X^2 (4) = 9.488, p = 0.422). The contingency table for this chi-squared test is shown in Table 14. However, it is important to note that there was twice the number of CHI events resulting in *Medium* levels of MPS reported in Bantam (n = 20) when compared to Pee Wee hockey (n = 10).

Table 14. Cross tabulation of age group and MPS categories.

	Categories of MPS levels				
	Very Low (< 8.0%)	**Low** (8 – 16.9%)	**Medium** (17 – 25.9%)	**High** (26 – 34.9%)	**Very High** (> 35%)
Pee Wee					
Observed Count	17	23	10	9	4
Expected Count	14.8	23.6	13.9	7.9	2.8
% within Age Group	27.0%	36.5%	15.9%	14.3%	6.3%
% within Event Type	53.1%	45.1%	33.3%	52.9%	66.7%
% of Total	12.5%	16.9%	7.4%	6.6%	2.9%
Std. Residual	0.6	-0.1	-1.0	0.4	0.7
Bantam					
Observed Count	15	28	20	8	2
Expected Count	17.2	27.4	16.1	9.1	3.2
% within Age Group	20.5%	38.4%	27.4%	11.0%	2.7%
% within Event Type	46.9%	54.9%	66.7%	47.1%	33.3%
% of Total	11.0%	20.6%	14.7%	5.9%	1.5%
Std. Residual	-0.5	0.1	1.0	-0.4	-0.7

** 2 cells have expected counts less than 5. The minimum expected count is 2.78.*

Other patterns can be found when the frequency of MPS magnitudes were further categorized by the different impact event types (Table 15). In Pee Wee hockey, half of the confirmed impacts that resulted in *Medium* levels of MPS were from head to ice events. Furthermore, of all of the head to ice events that occurred in Pee Wee, 70% (7/10) had MPS values in excess of 17% strain. Zero of the head to ice events across either Pee Wee or Bantam resulted in *Very Low* levels of MPS. In Bantam hockey, there were twice as many confirmed shoulder to head events with *Low* levels of MPS than in Pee Wee. More notably, there were also 17 Bantam shoulder to head events that resulted in *Medium* MPS magnitudes, in contrast to 0 of these events being reported at the Pee Wee level. Of all of the confirmed head impacts leading to *Medium* levels of MPS in Bantam, 85% (17/20) were from a shoulder to head event. However in Pee Wee, 54.5% (6/11) of the shoulder to head events that occurred resulted in *Very Low* magnitudes of MPS instead. Six confirmed Pee Wee elbow to head events had MPS values within the *Very Low* range and 9 had values in the *Low* MPS range. This was the opposite in Bantam, where 9 and 6 elbow to head events were found in the *Very Low* and *Low* categories of MPS respectively. While Pee Wee and Bantam had an equal number of head to boards events resulting in *High* MPS values, there were an additional 3 head to boards events in Pee Wee for both the *Medium* and *Very High* MPS magnitudes.

Table 15. Frequency of categorized maximum principal strain (MPS) magnitudes from confirmed head impacts, by event type.

	Very Low < 8.0%	**Low** 8.0 – 16.9%	**Medium** 17 – 25.9%	**High** 26 – 34.9%	**Very High** > 35%	**Total Impacts**
Head to Ice						
Pee Wee	0	3	5	1	1	**10**
Bantam	0	4	0	1	0	**5**
Shoulder to						
Pee Wee	6	5	0	4	0	**15**
Bantam	2	10	17	1	0	**30**
Elbow to Head						
Pee Wee	6	9	0	0	0	**15**
Bantam	9	3	0	0	0	**12**
Head to Head						
Pee Wee	5	3	2	0	0	**10**
Bantam	4	3	1	0	0	**8**
Head to Boards						
Pee Wee	0	3	3	4	3	**13**
Bantam	0	4	0	4	1	**9**
Head to Glass						
Pee Wee	0	0	0	0	0	**0**
Bantam	0	4	2	2	1	**9**

CHAPTER 5: DISCUSSION

Describing the magnitudes and frequencies associated with head impact events can assist researchers and policy-makers in developing a better understanding of the brain trauma risks at different ages of competition in youth hockey. The inclusion of body checking at the Bantam-level creates an important transition period in which there are changes to how the sport is being played. This can result in a shift to how brain trauma occurs as players are exposed to increased body contact while also becoming bigger, more skilled athletes (Black et al., 2017; Emery et al., 2010a). Brain trauma profiles for youth hockey athletes before and after this transition period have not yet been investigated. The purpose of this study was to describe and compare the head dynamic response, brain tissue deformation, and frequency of head impact events between competitive Pee Wee and Bantam-level hockey players.

5.1 Head Impact Magnitudes

5.1.1 Peak Linear and Rotational Accelerations

The mean peak linear and rotational acceleration magnitudes from exemplar head impact events in this study were below the thresholds for 25% concussion risk proposed by Zhang et al. (2004). However, peak linear and rotational acceleration magnitudes from head impact events were not found to be significantly different between Pee Wee and Bantam hockey. This is expected given the means and large standard deviations reported for these dependent variables within the two age groups. This wide spread of data may be explained due to the dynamic response magnitudes being collected across six unique impact event types and at wide range of impacting velocities. The type of impact event in hockey has been shown to have large effect on head dynamic response and brain tissue strains (Kendall et al., 2014; Kendall, 2016; Rousseau, 2014). As an example, previous injury reconstructions of head to ice falls have characterized this event with peak dynamic response values well above the threshold for 80% risk of mTBI (Kendall et al., 2012a; Zhang et al., 2004). Injurious shoulder and elbow events reconstructed at typical skating velocities in the NHL have also demonstrated peak dynamic response values exceeding 50% risk for mTBI (Kendall et al., 2014; Rousseau, 2014; Zhang et al., 2004). Including exemplar events from a range of different impact velocities and impact compliances also creates large variations in the dynamic response results (de Grau Amezcua, 2017; Hoshizaki et al., 2013). Therefore, using exemplar reconstructions from across distinct impact event types likely resulted in a greater spread of data for the dynamic response magnitudes.

The dynamic response magnitudes reported in this study may have also been influenced by similarities with the head impact characteristics between Pee Wee and Bantam. With the exception of the striking mass for some event types, the impact characteristics of the exemplar reconstructions were comparable between the two groups. The overall average of head impact velocities used for the exemplar reconstructions remained relatively consistent between both two groups across each of the velocity categories (Figure 17). Using the mean *calculated velocities*, or median velocity, within pre-defined velocity categories for the exemplars likely reduced between-group variations which may have been influenced by the impact velocities. Furthermore, the impact locations used for the exemplar reconstructions were also relatively consistent between Pee Wee and Bantam hockey. While the exact point of head contact varied slightly for each reconstruction, the exemplars were still categorized within the same overall impact locations. However, this is likely an accurate representation of the head impact events which occur at these two levels of play. Similarities in these aspects of the impact characteristics for both age groups may have contributed towards the lack of differences reported for the dynamic response magnitudes.

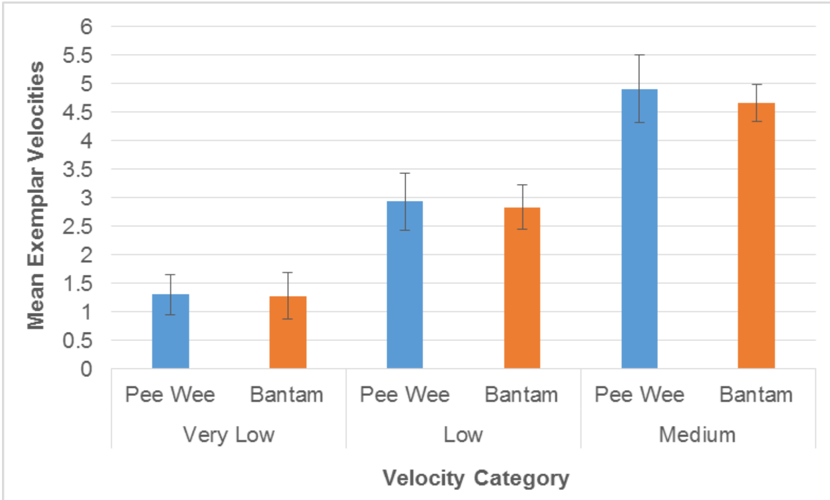


Figure 17. Mean impact velocities used for the exemplar reconstructions across very low, low, and medium velocity categories in Pee Wee and Bantam hockey.

The effective striking masses used for the shoulder and elbow impact reconstructions in this study were different between the two age groups. While there was only a 0.7 kg difference in striking mass for the elbow to head reconstructions, the striking mass for the shoulder to head reconstructions was 1.8 kg greater in Bantam than Pee Wee. Karton et al. (2014) conducted a study on the influence of impactor mass on dynamic response by using a pendulum system to strike a Hybrid III headform. It was reported that 2 kg differences in the striking mass created significant differences in both linear and rotational acceleration responses, for impacting masses up to 10.3 kg (Karton et al., 2014). However in this current study, there were no significant differences found in either peak linear ($p = 0.49$) or peak rotational accelerations ($p = 0.32$) when comparing shoulder to head events in Pee Wee to those in Bantam. It is important to note that Karton et al. (2014) conducted their impact reconstructions at a controlled impact velocity (4.0 m/s) while using an unhelmeted, adult-sized 50^{th} Hybrid III headform. However in hockey, the influence of impact compliance due to the helmet or shoulder pads would also contribute towards head kinematic responses and subsequent brain trauma risks (de Grau Amezcua, 2017; Kendall et al., 2014; Kendall, 2016; Post et al., 2014; Rousseau, 2014). Anthropometric differences between athletes in the Pee Wee and Bantam groups has been identified as a contributing risk factor to brain injuries such as concussion (Brust et al., 1992; Emery and Meeuwisse, 2006; Stuart et al., 1995; Willer et al., 2005). This has been reported within the context of body checking, due to increases in the frequency of player to player collisions when it is permitted in youth hockey (Bernard et al., 1993; Emery et al., 2010; King and Leblanc, 2006). The results of the current study would suggest that while mass can be an important contributing factor, differences in the athletes' weight alone may not fully account for the changes to brain trauma risks at the Pee Wee and Bantam age groups.

However, this study was not designed to investigate the effect of impact velocity, location, or mass on dynamic response. The purpose of this study was to describe and compare brain trauma risk profiles during an important transition period within youth hockey. The magnitudes of peak linear and rotational accelerations from head impact events in this study were not different between Pee Wee and Bantam hockey. While the comparison of head impact events using pre-defined exemplar categories may have influenced this result, it is important to recognize that the athletes at these age groups still share similarities in many of the key characteristics that contribute towards risk of brain trauma.

5.1.2 Maximum Principal Strain

There were also no statistically significant differences found between Pee Wee and Bantam for the mean peak MPS magnitudes from head impact events. The mean peak MPS magnitudes from head impact events were reported to be 18 percent for both age groups, which was below the 50% concussion risk thresholds reported by previous researchers (Kleiven, 2006; Zhang et al., 2004). Since these MPS magnitudes were calculated from the exemplar impact reconstructions, these similarities may have also been a result of the current research design. Future studies should consider a research design which incorporates all reported head impact events, without the use of pre-defined exemplar categories.

Nevertheless, the results of this study found that the overall magnitudes of linear acceleration, rotational acceleration, and MPS from head impact events in Pee Wee hockey were not significantly different from those occurring in Bantam hockey. This would suggest that the differences in brain trauma risks at these two age groups may not necessarily be due to head impact magnitudes. It also remains important to further consider the potential differences which may be created by the frequency of head impact events occurring in Pee Wee and Bantam-level hockey.

5.2 Head Impact Frequencies

5.2.1 Confirmed and Suspected Impacts

In this study, Pee Wee athletes were reported to experience 17.5 CHI events in 1000 player-hours, which was slightly greater than Bantam athletes at 15.1 CHI events in 1000 player-hours. There was no significant difference found in the frequency of CHI events per 1000 player-hours between these two age groups ($p = 0.56$). Due to the conservative nature of the inclusion criteria for this study, it is possible that the frequency of CHI events was underreported as the result of limitations with video picture quality. However, there were also no differences between Pee Wee and Bantam for either the frequency of SHI events per 1000 player-hours ($p = 0.22$), or the frequency of CBDHI events per 1000 player-hours ($p = 0.83$). This would suggest that the total frequency of head impact events remains relatively consistent between Pee Wee and Bantam hockey. Previous studies have reported that brain injury rates in youth hockey increase with age, and body checking has been identified as an important factor contributing to the risk of injury (Emery and Meeuwisse, 2006; Mölsä et al., 2003; Stuart et al., 1995; Willer et al., 2005). With the addition of body checking at the Bantam level, it was hypothesized in this study that there would be an increase in the number of reported head impact events when compared to Pee Wee. However, the null hypothesis was accepted and it is possible that changes in risks for brain injury may not necessarily be due to increased exposure to head impact events. While the overall frequency of head impact events were not reported to be different between Pee Wee and Bantam hockey, it is important to note that Bantam had longer duration games, potentially leading to increased time on ice and head impacts exposure for these athletes. Furthermore, the head impact frequencies of specific event types, and the risks associated with these events, is also likely a more important factor when characterizing the brain trauma risk profiles of Pee Wee and Bantam-level athletes.

5.2.2 Impact Event Types

Chi-squared tests determined that there was a significant association between the age group and the type of head impact event that was reported in this study. This is likely reflective of the competition environments that Pee Wee and Bantam athletes experience at their respective levels of play. As body checking is not permitted in Pee Wee, many of the head impact events at this age were not the result of deliberate contact. A majority of the head to ice events reported in this study were at the Pee Wee level. There were 2.22 confirmed head to ice events per 1000 player hours in Pee Wee, in comparison to 0.85 confirmed head to ice events per 1000 player hours in Bantam. Pee Wee athletes are earlier in their skill development, and may be more susceptible to losing control while skating and subsequently falling to the ice during gameplay (Honey, 1998; Montgomery, 1988). This would also be consistent with existing brain injury literature reporting that younger athletes are more likely to suffer concussion from falling events (Willer et al., 2004). Head to ice impacts in hockey have been identified as high risk events for concussion (Kendall, 2016). A greater frequency of this event type in Pee Wee is an important factor when comparing to the brain trauma found in Bantam. In addition, Pee Wee athletes were also more likely to experience head to boards impact events. Head to boards events in Pee Wee were reported to occur more frequently per 1000 player-hours (2.89 CHI/1000 player-hours) in comparison to either the head to boards (1.52 CHI/1000 player-hours), or the head to glass events (1.52 CHI/1000 player-hours) at the Bantam level. This may be further indicative that Pee Wee athletes are still developing their skating abilities, and the incidence of these higher risk events may be associated with accidents rather than deliberate contact. Nearly all of the CHI events reported in this study occurred within the range of typical skating velocities for both Pee Wee and Bantam athletes (Montgomery, 1988). However, the Pee Wee athletes are likely less skilled and coordinated than their older counterparts, and therefore more susceptible to brain trauma from events which are associated with unintentionally losing control during gameplay.

In contrast, a greater proportion of the shoulder to head, and head to glass impact events were associated with Bantam hockey. This may be attributed to an increase in deliberate player contact with the introduction of body checking at this level. Player to player collisions are more common which would explain the 2-fold increase in the frequency of shoulder to head events in Bantam when compared to Pee Wee (Emery et al., 2010b; Warsh et al., 2009). Similar to existing reports in adult hockey populations, head contact with the glass in Bantam was also typically initiated by player to player body contact during a check (Hutchison, 2011). This may explain why 0 CHI and only 3 SHI glass events were reported in Pee Wee, and further support the rationale that these athletes were typically falling when sustaining head impacts to the boards. In addition, there was also a significantly greater frequency of suspected head to glass events reported in Bantam when compared to Pee Wee. This may be associated with limitations of the video analysis, which made it difficult to confirm head impact events of this type. However, given the amount of player to player contact and collisions occurring around the glass due to body checking, it is unsurprising that a larger frequency of suspected head to glass events was also reported at the Bantam-level.

Interestingly, commensurate increases in the number of elbow to head, and head to head impact events were not observed when comparing between Pee Wee and Bantam (Figure 18). This may have positive implications as the rules of the game dictate that it is illegal to lead with the elbow as the point of contact during body checking (i.e., “elbowing”), in addition to the existing zero tolerance policies for head contact in youth hockey (Krolikowski et al., 2017). Previous body checking experience has been correlated with 33% reductions to injury rates for Bantam-level athletes (Emery et al., 2011). However, given similarities in the frequency of elbow to head and head to head events, it is possible that despite being introduced to body checking for the first time in Bantam, there were no particular increases in illegal body contact (i.e., elbowing) due to inexperience. This suggests that while it is important to enforce the rules of the game to protect the athletes, policies that mitigate illegal activity within the game may only partially help manage the risks that are associated with brain trauma in Pee Wee and Bantam hockey.

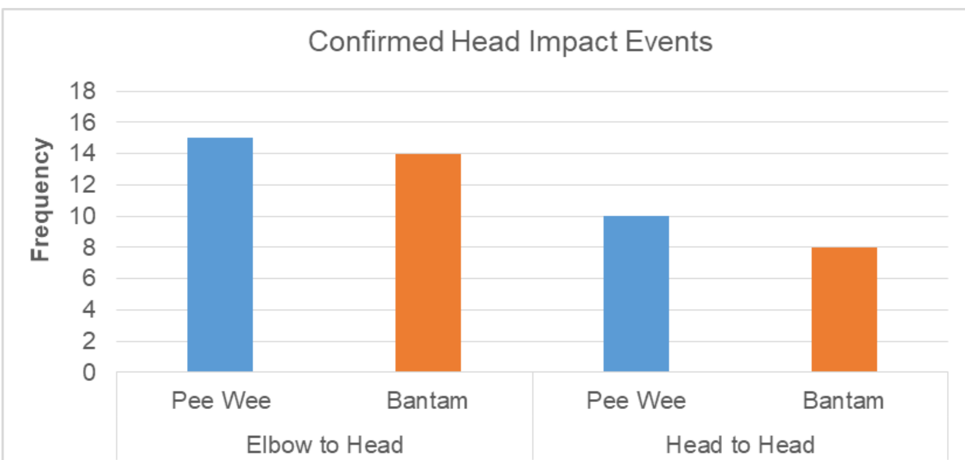


Figure 18. Frequency of confirmed head impact events in Pee Wee and Bantam for the elbow to head and head to head event types.

5.2.3 Maximum Principal Strain Categories

The frequency of reported MPS magnitudes were not found to be significantly associated with the age group of play. A majority of the head impact events in Pee Wee had *very low* or *low*

MPS magnitudes, while the majority of those in Bantam were *low* and *medium* MPS magnitudes. Most notably, there were twice as many events with *medium* levels of MPS (17 – 25.9%) reported in Bantam than there were in Pee Wee. 17/20 of all events *medium* MPS levels in Bantam were the result of shoulder to head impact events. Twice as many shoulder to head events resulting in *low* MPS magnitudes for Bantam were reported in comparison to Pee Wee (Figure 19).

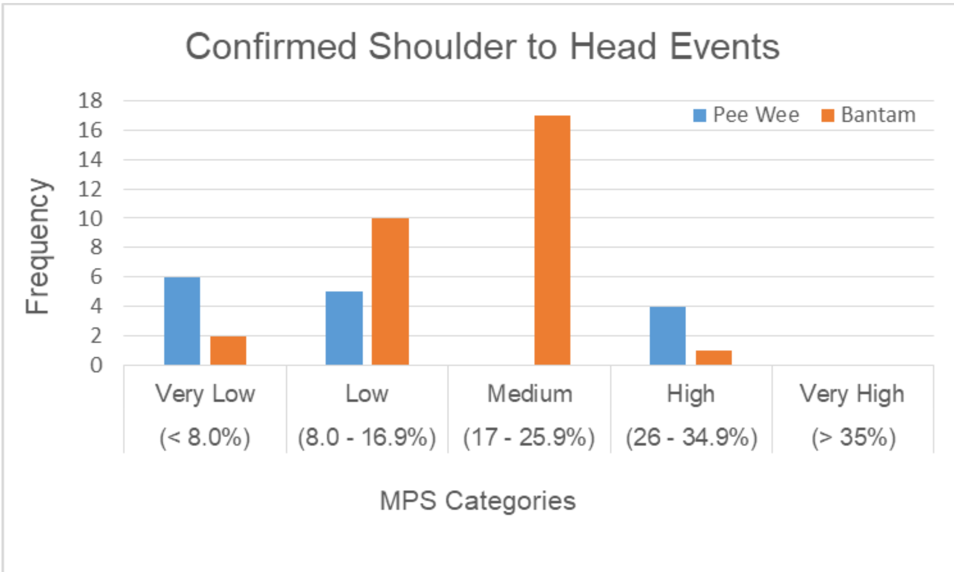


Figure 19. MPS magnitudes from confirmed shoulder to head events in Pee Wee and Bantam hockey, sorted by categories.

This would suggest that the frequency of shoulder to head events is an important differentiating factor to the brain trauma risk profiles of Pee Wee and Bantam athletes. For Pee Wee athletes, high risk head impact events were typically accidental in nature and involved the player falling to the ice or into the boards. This could also explain why Pee Wee athletes were reported to have a slightly greater frequency of *high* and *very high* MPS events than Bantam athletes in this study. However, the introduction of body checking in Bantam led to an increase in the frequency of shoulder to head events, which was associated with a greater number of MPS values within the range of concussion risk thresholds. Peak MPS levels of 0.19 and 0.24 have been associated with 50% and 80% risks for concussion in NFL football players (Zhang et al., 2004).

In adult hockey players, shoulder events with an MPS value of 0.30 has been correlated with a 50% risk of concussion (Rousseau, 2014). However, youth have also been reported to be more vulnerable to concussion from lower levels of brain tissue strain (Dawson, 2016). While the overall magnitude and total frequency of head impact events were similar between groups, there is a discernible shift in how head impacts are sustained in terms of the impact event type. The higher frequency of shoulder to head events from body checking may be important in creating greater risks for brain injury within Bantam-level hockey. The results of this study provides evidence supporting that head impact events due to body checking is associated with increased brain injury risk in youth hockey populations (Black et al., 2017; Emery et al., 2010; Marchie and Cusimano, 2003; Warsh et al., 2009).

5.3 Implications

The age at which body checking should be introduced to youth hockey remains an important topic for debate. Despite reported differences in injury rates, many of the physical traits and head impact characteristics are similar between Pee Wee and Bantam athletes. This study suggests that it is differences in the frequency of specific head impact event types which create changes to the brain trauma risks within youth hockey. Deliberate player to player contact from body checking exposes athletes to increased impact events associated with higher levels of MPS and subsequent risks for brain injury. Recent research found that removing body checking from Pee Wee hockey has led to a reduction in the rate of concussion by 64% (Black et al., 2017). Given the effectiveness of this strategy, it may be worthy for policy-makers to consider further delaying the introduction of body checking to the Midget-level (ages 15-17).

However, body checking remains an integral skill with important strategic values within the sport of hockey. Ensuring that athletes learn how to properly and safely execute this skill has been posed as a common counterargument to this issue (King and Leblanc, 2006; Marchie and Cusimano, 2003). Enforcement of zero-tolerance for head contact policies have had limited effectiveness in mitigating concussion risks (Krolikowski et al., 2017), and results of the current study suggest that illegal on-ice activity does not differ between Pee Wee and Bantam. Therefore, changes to the brain trauma profiles during this important transition period can likely be attributed to the inherent risks which are associated with the skill of body checking itself. However, body checking literature and discourse in youth hockey has primarily focused on either fully incorporating or eliminating this skill at different levels of play (Black et al., 2017; Emery et al., 2010b; King and Leblanc, 2006; Marchie and Cusimano, 2003). It is possible that a more gradual integration of body contact into the competition environment (e.g. progressing from no contact, to some forms of deliberate contact, to full body checking) may be a more effective strategy for reducing risks of brain trauma than current existing “all-or-nothing” policies.

Adapting coaching strategies may be another approach for reducing potential brain trauma risks in youth hockey. Given that Pee Wee athletes more frequently sustain head impacts from events which are associated with losing control and falling, it may be beneficial to focus more training on skating abilities and improving these young athletes’ core strength and balance (Montgomery, 1988). In addition to improving an athlete’s visuospatial awareness (e.g. “learning” how to fall properly) during practices, this may help prevent potential brain injuries sustained by falling to the ice or into the boards.

Future researchers should also consider ways to improve hockey equipment, such as helmets, to better protect against the different types of head impact events more commonly reported at specific ages of competition. For instance, Kendall et al. (2014) demonstrated that shoulder pad design could be a potential strategy for decreasing peak dynamic response magnitudes during head impacts. Furthermore, the characteristics of head impact events and its associated brain trauma risks can help guide the development of protective helmet technologies tailored towards specific ages and levels of play (Bishop et al., 2014; Hoshizaki et al., 2014; Kendall, 2016; Nur et al., 2015; Rousseau, 2014). By better understanding the circumstances contributing towards brain trauma risk in youth hockey, it will further help all stakeholders involved, including coaches, athletes, policymakers, and innovators, to mitigate these risks and protect young athletes participating within contact sports.

CHAPTER 6: CONCLUSION

The objective of this study was to compare brain trauma profiles between Pee Wee and Bantam hockey, as characterized by the dynamic response, MPS, and frequency of head impact events. There were no differences in the overall peak linear acceleration, peak rotational acceleration, or peak MPS magnitudes from head impact events between Pee Wee and Bantam. The overall frequency of head impact events were also similar between groups. However, age level was significantly associated with the type of head impact events reported in this study. Head to ice and head to boards impact events were more common in Pee Wee, while shoulder to head and head to glass impact events were more common in Bantam. This shift in the frequency of different head impact events may be associated with the introduction of body checking in Bantam, which fundamentally changes how the sport of hockey is played. This had important implications for the frequency of MPS magnitudes experienced by these athletes. A greater frequency of shoulder to head impact events was associated with an increase in MPS magnitudes within concussion range for Bantam hockey. Describing the characteristics of how brain trauma occurs help inform future protective and preventative strategies to protect young athletes in contact sports, such as hockey. With increasing attention focused on the potential short- and long-term effects of brain trauma exposure, it has become increasingly important to quantify and gain a better of understanding of brain trauma in youth sports. Policy changes can affect how sports are played and how athletes are exposed to brain trauma. Furthermore, development of age-specific protective equipment may better protect against the unique brain trauma risks experienced by athletes at different levels of competition. A combination of regulatory and technological strategies may be most appropriate for managing brain trauma risks and future brain health in youth hockey.

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APPENDICES

Appendix A

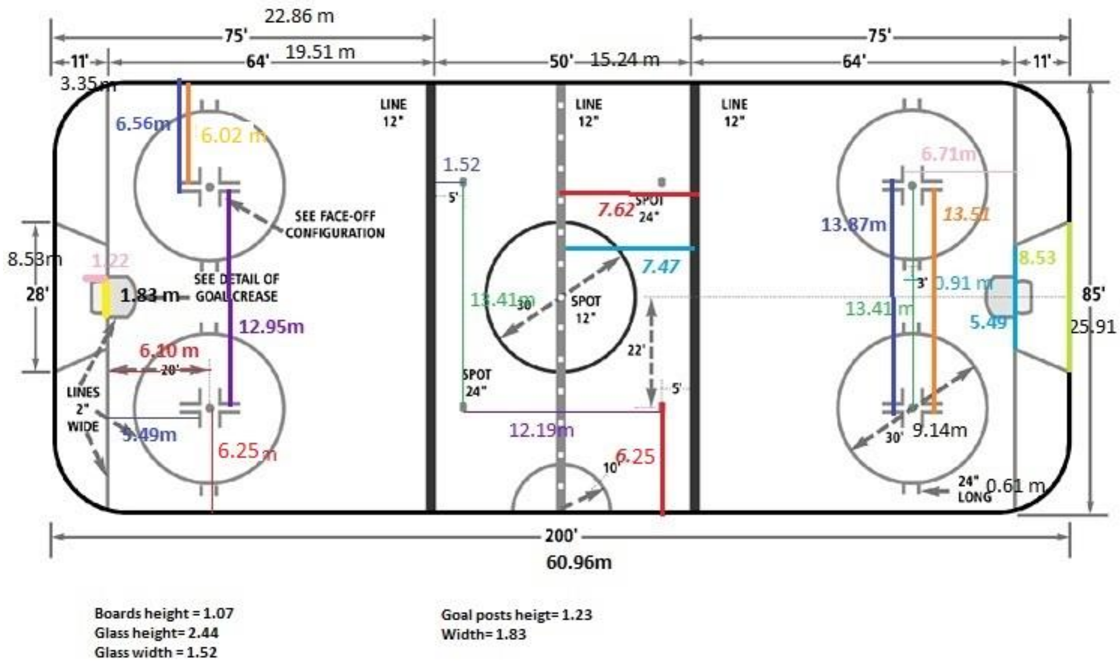


Figure 20. Rink dimensions and ice surface measurements for an NHL-sized hockey rink.

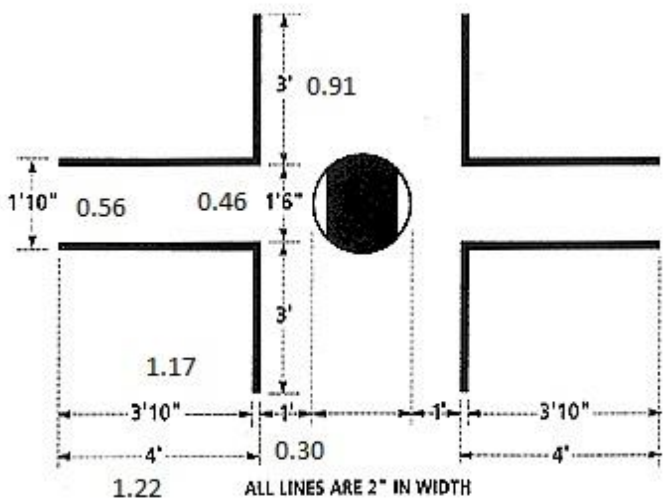


Figure 21. Face-off circle measurements for an NHL-sized hockey rink.

Appendix B

Table 16. Impact velocities calculated using Kinovea to determine the target velocities for exemplar impact reconstructions, head to ice events.

Exemplar Reconstruction	Targeted Velocity	Confirmed Head Impact	Kinovea Trial 1 (m/s)	Kinovea Trial 2 (m/s)	Kinovea Trial 3 (m/s)	Kinovea Average (m/s)
PW-I-1	1.19 m/s					
		CHI #1	*1.13*	*1.25*	-	*1.19*
PW-I-2	1.38 m/s					
		CHI #1	*1.00*	*1.00*	-	*1.00*
		CHI #2	*1.75*	*1.75*	-	*1.75*
PW-I-3	1.63 m/s					
		CHI #1	*1.63*	*1.63*	-	*1.63*
PW-I-4	3.00 m/s					
		CHI #1	*3.00*	*3.00*	-	*3.00*
PW-I-5	3.06 m/s					
		CHI #1	*2.50*	*3.25*	-	*2.88*
		CHI #2	*3.50*	*3.00*	-	*3.25*
		CHI #3	-	-	-	*Estimated*
PW-I-6	4.75 m/s					
		CHI #1	*4.50*	*5.00*	-	*4.75*
PW-I-7	4.00 m/s					
		CHI #1	*4.25*	*3.75*	-	*4.00*
BN-I-1	0.38 m/s					
		CHI #1	*0.38*	*0.38*	-	*0.38*
BN-I-2	2.13 m/s					
		CHI #1	*2.25*	*2.00*	-	*2.13*
BN-I-3	3.00 m/s					
		CHI #1	*3.00*	*3.00*	-	*3.00*
		CHI #2	-	-	-	*Estimated*
		CHI #3	-	-	-	*Estimated*

Table 17. Impact velocities calculated using Kinovea to determine the target velocities for exemplar impact reconstructions, shoulder to head events.

Exemplar Reconstruction	Targeted Velocity	Confirmed Head Impact	Kinovea Trial 1 (m/s)	Kinovea Trial 2 (m/s)	Kinovea Trial 3 (m/s)	Kinovea Average (m/s)
PW-S-1	1.73 m/s					
		CHI #1	*1.50*	*1.95*	-	*1.73*
		CHI #2	-	-	-	*Estimated*
PW-S-2	1.70 m/s					
		CHI #1	*1.70*	*1.70*	-	*1.70*
PW-S-3	1.00 m/s					
	(median)	*CHI #1*	-	-	-	*Estimated*
		CHI #2	-	-	-	*Estimated*
PW-S-4	0.85 m/s					
		CHI #1	*0.90*	*0.75*	-	*0.83*
		CHI #2	-	*0.85*	*0.90*	*0.88*
PW-S-5	2.53 m/s					
		CHI #1	*2.15*	*2.90*	-	*2.53*
PW-S-6	2.28 m/s					
		CHI #1	*2.10*	*2.20*	-	*2.15*
		CHI #2	*2.00*	*2.30*	-	*2.15*
		CHI #3	*2.45*	*2.60*	-	*2.53*
PW-S-7	5.28 m/s					
		CHI #1	*5.75*	*5.05*	-	*5.40*
		CHI #2	*4.25*	*4.69*	-	*4.47*
		CHI #3	*6.15*	*5.80*	-	*5.98*
PW-S-8	5.80 m/s					
		CHI #1	*5.60*	*6.00*	-	*5.80*
BN-S-1	1.44 m/s					
		CHI #1	*1.20*	*0.80*	-	*1.00*
		CHI #2	*1.95*	*1.80*	-	*1.88*
		CHI #3	-	-	-	*Estimated*
BN-S-2	1.33 m/s					
		CHI #1	*1.55*	*1.10*	-	*1.33*
		CHI #2	-	-	-	*Estimated*
BN-S-3	3.23 m/s					
		CHI #1	*2.65*	*2.60*	-	*2.63*
		CHI #2	*2.65*	*3.15*	-	*2.90*
		CHI #3	*3.15*	*3.15*	-	*3.15*
		CHI #4	*3.25*	*3.15*	-	*3.20*
		CHI #5	*3.50*	*3.45*	-	*3.48*
		CHI #6	*3.30*	*3.75*	-	*3.53*
		CHI #7	*3.50*	*4.00*	-	*3.75*
		CHI #8	-	-	-	*Estimated*
		CHI #9	-	-	-	*Estimated*
		CHI #10	-	-	-	*Estimated*
BN-S-4	2.85 m/s					
		CHI #1	*2.55*	*2.60*	-	*2.85*
		CHI #2	*3.05*	*2.70*	-	*2.88*

		CHI #3	*3.05*	*2.75*	-	*2.90*
		CHI #4	*3.30*	*2.80*	-	*3.05*
		CHI #5	-	-	-	*Estimated*
BN-S-5	3.00 m/s (median)	*CHI #1*	-	-	-	*Estimated*
BN-S-6	4.98 m/s					
		CHI #1	*4.30*	*4.35*	-	*4.33*
		CHI #2	*5.00*	*5.20*	-	*5.10*
		CHI #3	*5.20*	*5.10*	-	*5.15*
		CHI #4	*5.25*	*5.45*	-	*5.35*
BN-S-7	4.21 m/s					
		CHI #1	*3.75*	*4.35*	-	*4.05*
		CHI #2	*3.94*	*4.81*	-	*4.38*
BN-S-8	5.00 m/s (median)	*CHI #1*	-	-	-	*Estimated*
BN-S-9	5.00 m/s					
		CHI #1	*5.30*	*4.70*	-	*5.00*
BN-S-10	6.45 m/s					
		CHI #1	*6.58*	*6.31*	-	*6.45*

Table 18. Impact velocities calculated using Kinovea to determine the target velocities for exemplar impact reconstructions, elbow to head events.

Exemplar Reconstruction	Targeted Velocity	Confirmed Head Impact	Kinovea Trial 1 (m/s)	Kinovea Trial 2 (m/s)	Kinovea Trial 3 (m/s)	Kinovea Average (m/s)
PW-E-1	1.50 m/s					
		CHI #1	*1.50*	*1.50*	-	*1.50*
PW-E-2	1.00 m/s					
		CHI #1	*1.10*	*0.90*	-	*1.00*
PW-E-3	1.25 m/s					
		CHI #1	*1.30*	*1.20*	-	*1.25*
		CHI #2	-	-	-	*Estimated*
		CHI #3	-	-	-	*Estimated*
PW-E-4	0.80 m/s					
		CHI #1	*0.70*	*0.90*	-	*0.90*
PW-E-5	3.30 m/s					
		CHI #1	*3.20*	*3.40*	-	*3.30*
PW-E-6	2.76 m/s					
		CHI #1	*2.30*	*2.35*	-	*2.33*
		CHI #2	*2.80*	*1.90*	-	*2.35*
		CHI #3	*3.50*	*3.70*	-	*3.60*
PW-E-7	2.18 m/s					
		CHI #1	*2.00*	*2.20*	-	*2.10*
		CHI #2	*2.75*	*1.55*	-	*2.15*
		CHI #3	-	*2.45*	*2.15*	*2.30*
PW-E-8	5.15 m/s					
		CHI #1	*5.25*	*5.05*	-	*5.15*
PW-E-9	4.40 m/s					
		CHI #1	*4.55*	*4.25*	-	*4.40*
BN-E-1	1.00 m/s					
	(median)	*CHI #1*	-	-	-	*Estimated*
		CHI #2	-	-	-	*Estimated*
BN-E-2	1.75 m/s					
		CHI #1	*1.65*	*1.85*	-	*1.75*
BN-E-3	2.30 m/s					
		CHI #1	*2.65*	*1.95*	-	*2.30*
		CHI #2	-	-	-	*Estimated*
BN-E-4	2.75 m/s					
		CHI #1	*2.60*	*2.25*	-	*2.43*
		CHI #2	*2.85*	*2.10*	-	*2.48*
		CHI #3	*3.25*	*3.45*	-	*3.35*
		CHI #4	-	-	-	*Estimated*
BN-E-5	4.53 m/s					
		CHI #1	*4.35*	-	*3.90*	*4.13*
		CHI #2	*4.60*	*4.40*	-	*4.50*
		CHI #3	*5.10*	*4.80*	-	*4.95*
BN-E-6	9.08 m/s					
		CHI #1	*9.20*	*8.95*	-	*9.08*

Table 19. Impact velocities calculated using Kinovea to determine the target velocities for exemplar impact reconstructions, head to head events.

Exemplar Reconstruction	Targeted Velocity	Confirmed Head Impact	Kinovea Trial 1 (m/s)	Kinovea Trial 2 (m/s)	Kinovea Trial 3 (m/s)	Kinovea Average (m/s)
PW-H-1	1.00 m/s (median)	*CHI #1*	-	-	-	*Estimated*
PW-H-2	1.38 m/s					
		CHI #1	*1.15*	*1.60*	-	*1.38*
		CHI #2	*1.15*	*1.60*	-	*1.38*
PW-H-3	1.00 m/s (median)	*CHI #1*	-	-	-	*Estimated*
PW-H-4	3.93 m/s					
		CHI #1	*3.85*	*4.00*	-	*3.93*
		CHI #2	-	-	-	*Estimated*
PW-H-5	3.00 m/s (median)	*CHI #1*	-	-	-	*Estimated*
PW-H-6	3.93 m/s					
		CHI #1	*3.85*	*4.00*	-	*3.93*
		CHI #2	-	-	-	*Estimated*
PW-H-7	3.00 m/s (median)	*CHI #1*	-	-	-	*Estimated*
BN-H-1	1.69 m/s					
		CHI #1	*1.70*	*1.60*	-	*1.65*
		CHI #2	*1.70*	*1.60*	-	*1.65*
		CHI #3	*1.80*	*1.65*	-	*1.73*
		CHI #4	*1.80*	*1.65*	-	*1.73*
BN-H-2	2.19 m/s					
		CHI #1	*2.25*	*2.13*	-	*2.19*
BN-H-3	3.25 m/s					
		CHI #1	*3.30*	*3.20*	-	*3.25*
		CHI #2	*3.30*	*3.20*	-	*3.25*
BN-H-4	2.19 m/s					
		CHI #1	*2.25*	*2.13*	-	*2.19*

Table 20. Impact velocities calculated using Kinovea to determine the target velocities for exemplar impact reconstructions, head to boards events.

Exemplar Reconstruction	Targeted Velocity	Confirmed Head Impact	Kinovea Trial 1 (m/s)	Kinovea Trial 2 (m/s)	Kinovea Trial 3 (m/s)	Kinovea Average (m/s)
PW-B-1	1.98 m/s					
		CHI #1	*1.95*	*2.00*	-	*1.98*
		CHI #2	-	-	-	*Estimated*
PW-B-2	1.58 m/s					
		CHI #1	*1.35*	*1.80*	-	*1.58*
		CHI #2	-	-	-	*Estimated*
		CHI #3	-	-	-	*Estimated*
PW-B-3	2.33 m/s					
		CHI #1	*2.60*	*2.05*	-	*2.33*
PW-B-4	2.73 m/s					
		CHI #1	*1.85*	*2.40*	-	*2.13*
		CHI #2	*3.25*	*3.40*	-	*3.33*
		CHI #3	-	-	-	*Estimated*
PW-B-5	3.38 m/s					
		CHI #1	*3.30*	*3.45*	-	*3.38*
PW-B-6	5.00 m/s					
	(median)	*CHI #1*	-	-	-	*Estimated*
		CHI #2	-	-	-	*Estimated*
		CHI #3	-	-	-	*Estimated*
BN-B-1	1.38 m/s					
		CHI #1	*1.20*	*1.55*	-	*1.38*
		CHI #2	-	-	-	*Estimated*
BN-B-2	1.28 m/s					
		CHI #1	*1.05*	*1.50*	-	*1.28*
		CHI #2	-	-	-	*Estimated*
BN-B-3	3.00 m/s					
	(median)	*CHI #1*	-	-	-	*Estimated*
		CHI #2	-	-	-	*Estimated*
BN-B-4	2.98 m/s					
		CHI #1	*2.50*	*2.55*	-	*2.53*
		CHI #2	*3.35*	*3.50*	-	*3.43*
BN-B-5	4.58 m/s					
		CHI #1	*4.55*	*4.60*	-	*4.58*

Table 21. Impact velocities calculated using Kinovea to determine the target velocities for exemplar impact reconstructions, head to glass events.

Exemplar Reconstruction	Targeted Velocity	Confirmed Head Impact	Kinovea Trial 1 (m/s)	Kinovea Trial 2 (m/s)	Kinovea Trial 3 (m/s)	Kinovea Average (m/s)
BN-G-1	1.30 m/s					
		CHI #1	*1.50*	*1.10*	-	*1.30*
BN-G-2	3.00 m/s					
	(median)	*CHI #1*	-	-	-	*Estimated*
BN-G-3	3.00 m/s					
	(median)	*CHI #1*	-	-	-	*Estimated*
		CHI #2	-	-	-	*Estimated*
BN-G-4	3.00 m/s					
	(median)	*CHI #1*	-	-	-	*Estimated*
BN-G-5	3.36 m/s					
		CHI #1	*4.10*	*3.30*	-	*3.70*
		CHI #2	*3.20*	*2.85*	-	*3.03*
BN-G-6	3.00 m/s					
	(median)	*CHI #1*	-	-	-	*Estimated*
BN-G-7	4.35 m/s					
		CHI #1	*4.40*	*4.30*	-	*Estimated*

Appendix C

Sample impact construction report, with Kinovea velocity calculations and reconstruction setup.

NiSL

IMPACT RECONSTRUCTION REPORT

EVENT DETAILS

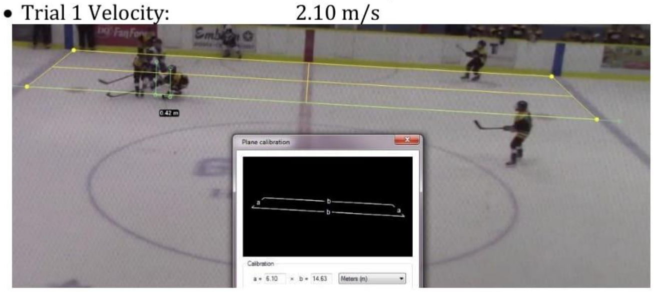
Reconstruction ID: **PW-S-6**
Level of play: Peewee Boys
Event type: Shoulder to head
Velocity category: Low
Impact location: Side
Confirmed Impact? Yes

VIDEO ANALYSIS

1. PeeweeAA-Oct23-YR1-Game2-WC-2-11b
   - Can Kinovea? Yes
   - Rink: Navan Arena
   - Impact location: Side – D (right)
   - **Impact velocity:** **2.15 m/s**

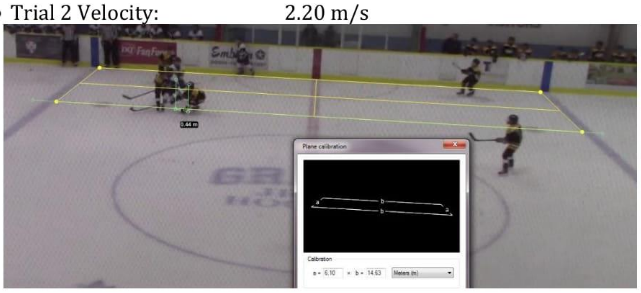
Trial 1

- Distance to impact: 0.42m
- # of frames used: 5 (t = 0.2s)
- Trial 1 Velocity: 2.10 m/s



Trial 2

- Distance to impact: 0.44m
- # of frames used: 5 (t = 0.2s)
- Trial 2 Velocity: 2.20 m/s



1

IMPACT RECONSTRUCTION REPORT

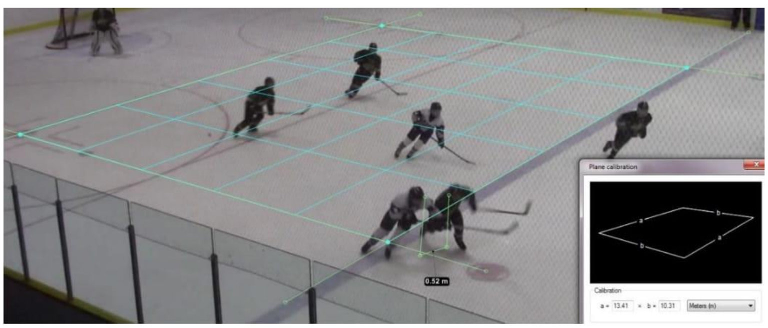
2. PeeweeAA-Jan24-YR1-Game4-AM-1-9
   - Can Kinovea? Yes
   - Rink: Navan Arena
   - Impact location: Side – C (right)
   - **Impact velocity: 2.53 m/s**

Trial 1

- Distance to impact: 0.49m
- # of frames used: 5 (t = 0.2s)
- Trial 1 Velocity: 2.45 m/s

Trial 2

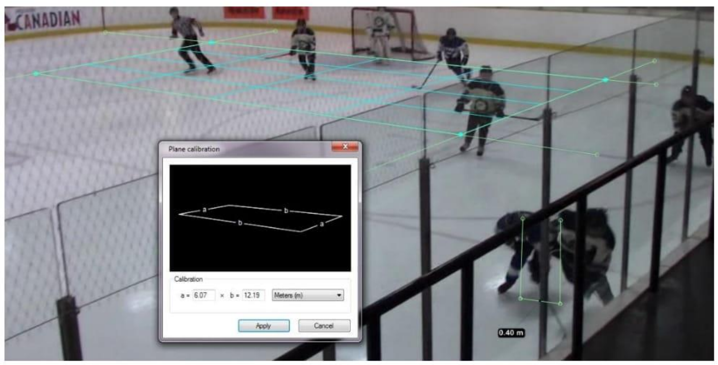
- Distance to impact: 0.52m
- # of frames used: 5 (t = 0.2s)
- Trial 1 Velocity: 2.60 m/s



3. <u>CumberlandPeewee-Nov6-YR1-Game3-AM-1-6</u>
    - Can Kinovea? Yes
    - Rink: Richcraft Sensplex (JP Potvin Arena)
    - Impact location: Side – C (left)
    - **Impact velocity: 2.15 m/s**

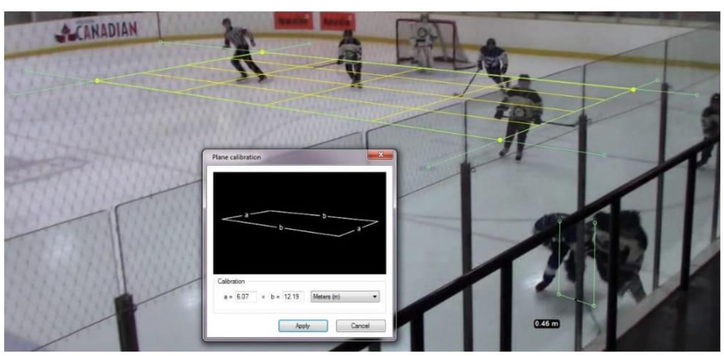
Trial 1

- Distance to impact: 0.40m
- # of frames used: 5 (t = 0.2s)
- Trial 1 Velocity: 2.00 m/s



Trial 2

- Distance to impact: 0.46m
- # of frames used: 5 (t = 0.2s)
- Trial 1 Velocity: 2.30 m/s



IMPACT RECONSTRUCTION REPORT

RECONSTRUCTION SETUP

Date of recon: March 4th, 2018

Headform: 5th Hybrid III headform

Neck: Unbiased Hybrid III neck

Helmet (cage): CCM Tacks 110 (FM580)

Impactor: 7.2kg pendulum with Reebok11k shoulder pad and VN foam cap

Target velocity: 2.28 m/s

Impact location: Side (right)

Setup photos:

RECONSTRUCTION RESULTS

	Reconstruction Velocity	Linear Acceleration (g)	Rotational Acceleration (rad/s^2)	Maximum Principle Strain
Trial 1	2.20	10.8	1089.1	0.06
Trial 2	2.19	10.3	1013.8	0.11
Trial 3	2.19	10.9	1181.0	0.13
Mean		**10.7 g**	**1094.6 rad/s^2**	**0.10**