Effect of rule changes occurring between 2003 and 2016 on head impact frequency and brain strain magnitude in North American professional ice hockey

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Abstract

Head impacts can result in various levels of brain trauma, from mild to severe, and often result in long lasting effects on human brain function (McAllister & McCrea, 2017; Sollmann et al., 2018). Over the past two decades alone the National Hockey League (NHL) has made several rule changes to the game (Marek, 2015; National Hockey League Official Rules 2010–11, 2010; National Hockey League Official Rules 2011–12, 2011; National Hockey League Official Rules 2014-15, 2014). Frequency and magnitude are needed to examine brain trauma as examining brain trauma solely on magnitude does not capture a full brain trauma profile or the long-term consequences of repetitive brain strain; higher frequencies at lower magnitudes of strain may result in long-term neurologic complications. The purpose of this study was to compare frequency of head impacts and frequency-magnitude of brain strain between the 2003-04 and 2016-17 seasons of North American professional ice hockey. Videos of head impact events from twenty 2003-04 and twenty 2016-17 regular season NHL games were analyzed. Head impact conditions were characterized by events type, inbound velocity, location and elevation, and reconstructed using physical and finite element model methods. Overall frequency of head impacts was similar between the two seasons. Head-to-glass had the highest frequency for event type in both seasons. Mann-Whitney U tests found there was a significant decrease in glove-to-head impact events in the 2016-17 season compared to the 2003-04 (U=111, p=0.009). There was also a significant decrease in the frequency of fight events in 2003-04 during regulation time when compared to 2016-17 (U=86, p<0.001). A significant increase in the frequency of head impacts within the low MPS level was found in the 2016-17 season compared to 2003-04 (U=130, p=0.050). Given the popularity of ice hockey nationally, continentally, and globally, the results of this study provide a better understanding of frequency of head impacts and magnitude of brain strain, allowing stakeholders to make informed decisions involving repetitive brain strain during the game and give insight in the effectiveness of rules involving head contact. Future studies should consider including the effect of rule changes on overtime and pre- and post-season game play compared to in-season games.

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CHAPTER 1: INTRODUCTION

1.1 Problem Statement

The speed and physicality of ice hockey athletes competing within an enclosed field of play presents an intrinsic risk for injury from an increased exposure to head impacts (Delaney, 2014). Head impacts often result in long lasting effects on the human brain, altering structural, functional, and metabolic characteristics of the brain (McAllister & McCrea, 2017; Sollmann et al., 2018). Concussions account for approximately 13% of all sports-related injuries (Kontos et al., 2016), and are the most common injury in collegiate ice hockey (Flik, Lyman, & Marx, 2005). Moreover, repetitive low-magnitude strains from head impacts have been shown to change brain function and structure (McAllister et al., 2014).

Impacting the head causes brain tissue deformation from acceleration or deceleration of the brain inside the skull (Ommaya & Gennarelli, 1974; Gurdjian et al., 1964). Brain trauma can be defined by the frequency of head impacts and magnitude of brain strain. Increased frequency of head impacts has been reported to increase the risk of negative health effects, including neurological damage and chronic brain disease (Hoshizaki et al., 2013). A full brain trauma profile required both frequency and magnitude to be documented, as magnitude alone does not capture the full exposure to brain injury or the long-term consequences. It has been proposed that brain tissue deformation measurements are a better predictor for risk of brain injury than linear or rotational acceleration alone (King, Yang, Zhang, & Hardy, 2003; Kimpara & Iwamoto, 2011; Post, Hoshizaki, & Gilchrist, 2011; Post & Hoshizaki, 2015). Maximum principal strain (MPS) has been demonstrated to have a close association with brain tissue strain and has the closest comparison of mechanical failure in anatomical testing (Post & Hoshizaki, 2015; Post & Hoshizaki, 2012; Hoshizaki et al., 2014; McAllister et al., 2012).

In an attempt to reduce the incidence of injuries, rule changes have been implemented in a variety of sports, including American football (Stemper et al., 2019), rugby (Hendricks, Lambert, Brown, Readhead, & Viljoen, 2014), cheerleading (Yau et al., 2019) and ice hockey (Donaldson, Asbridge, & Cusimano, 2013). Changes or additions to rules have had varying degrees of effectiveness in sport, from a decrease in head injury and concussion (Ruestow, Duke, Finley, & Pierce, 2015; Beaudouin, Aus der Fünten, Tröß, Reinsberger, & Meyer, 2019), to no effect (Donaldson, Asbridge, & Cusimano, 2013).

In the past two decades, the National Hockey League (NHL) has made several rule changes to the game (Marek, 2015; Donaldson, Asbridge, & Cusimano, 2013; National Hockey League Official Rules 2010–11, 2010; National Hockey League Official Rules 2011–12, 2011). Marek (2015) described two main reasons for rule changes in ice hockey: safety of players and spectators, and attractiveness of matches. During the 2005 Lockout in the NHL, a group of rules were added and/or modified to improve the attractiveness of the game, including redefining lines on the ice, penalties for fighting, and removal of the 2-Line Pass Rule (Marek, 2015). In 2010, the NHL introduced Rule 48 which made targeting an opponent's head from the blind side illegal (Donaldson, Asbridge, & Cusimano, 2013; National Hockey League Official Rules 2010–11, 2010), and was modified in 2011-12 to encompass all hits to the head (Donaldson, Asbridge, & Cusimano, 2013; National Hockey League Official Rules 2011–12, 2011). Rule changes to the field of play have the ability to influence how and where players move, which in turn influences player-to-player and player-to-object contact, and therefore, head impacts. Penalizing the targeting of an opponent's head should decrease the frequency of head impacts.

There continues to be a paucity of information reporting the frequency of head impact events comparing before and after the numerous rule changes since 2005. A comparison in brain trauma measurement between these two seasons will provide an analysis of how the rules have made a difference to risk of head injury in professional ice hockey.

1.2 Research Question

Have the changes in rules between 2003 and 2016 had an influence on the frequency of head impacts and magnitude of brain strain sustained during game play in North American ice hockey?

1.3 Objectives

1) To compare overall frequency of head impacts per game between 2003-04 and 2016-17 North American professional ice hockey games.
2) To compare frequency of impact event types between 2003-04 and 2016-17 North American professional ice hockey games.
3) To compare frequency of magnitude (MPS) categories between 2003-04 and 2016-17 North American professional ice hockey games.
4) To compare frequency of magnitude (MPS) categories of all reconstructed impact event types between 2003-04 and 2016-17 North American professional ice hockey games.

1.4 Purpose

<u>The purpose was to identify differences in head impact frequency and magnitude of brain strain for head impact events during regular season game play between the 2003 and 2016 North American professional ice hockey seasons due to rule changes that occurred between these two seasons.</u>

1.5 Independent Variables

1) Season of professional ice hockey
    a. 2003-04

    b. 2016-17

2) Impact event
    a. Head-to-ice
    b. Head-to-boards
    c. Head-to-glass
    d. Head-to-head
    e. Shoulder-to-head
    f. Elbow-to-head
    g. Glove-to-head
    h. Puck
    i. Stick
    j. Other
    k. Punch
    l. Fights
    m. Scrums

1.6 Dependent Variables

1) Impact Frequency
2) Impact Magnitude (Maximum Principal Strain (MPS) categories)
    a. Very low
    b. Low
    c. Moderate
    d. High
    e. Very high

1.7 Null Hypothesis

1) There will be no difference in the overall frequency of head impacts per game between professional ice hockey 2003-04 and 2016-17 seasons.
2) There will be no difference in the frequency of *head-to-glass* event types in regular game play between the 2003-04 and 2016-17 seasons.
3) There will be no difference in the frequency of *head-to-boards* event types in regular game play between the 2003-04 and 2016-17 seasons.
4) There will be no difference in the frequency of *head-to-ice* event types in regular game play between the 2003-04 and 2016-17 seasons.
5) There will be no difference in the frequency of *head-to-head* event types in regular game play between the 2003-04 and 2016-17 seasons.
6) There will be no difference in the frequency of *shoulder-to-head* event types in regular game play between the 2003-04 and 2016-17 seasons.
7) There will be no difference in the frequency of *elbow-to-head* event types in regular game play between the 2003-04 and 2016-17 seasons.
8) There will be no difference in the frequency of *glove-to-head* event types in regular game play between the 2003-04 and 2016-17 seasons.
9) There will be no difference in the frequency of *puck* event types in regular game play between the 2003-04 and 2016-17 seasons.
10) There will be no difference in the frequency of *stick* event types in regular game play between the 2003-04 and 2016-17 seasons.
11) There will be no difference in the frequency of *other* event types in regular game play between the 2003-04 and 2016-17 seasons.

12) There will be no difference in the frequency of *punch* event types in regular game play between the 2003-04 and 2016-17 seasons.
13) There will be no difference in the frequency of *fights* event types in regular game play between the 2003-04 and 2016-17 seasons.
14) There will be no difference in the frequency of *scrums* event types in regular game play between the 2003-04 and 2016-17 seasons.
15) There will be no difference in the frequency in the very low MPS level between the 2003-04 and 2016-17 seasons.
16) There will be no difference in the frequency in the low MPS level between the 2003-04 and 2016-17 seasons.
17) There will be no difference in the frequency in the moderate MPS level between the 2003-04 and 2016-17 seasons.
18) There will be no difference in the frequency in the high MPS level between the 2003-04 and 2016-17 seasons.
19) There will be no difference in the frequency in the very high MPS level between the 2003-04 and 2016-17 seasons.
20) There will be no difference in the frequency in any MPS level of *head-to-glass* event types in regular game play between the 2003-04 and 2016-17 seasons.
21) There will be no difference in the frequency in any MPS level of *head-to-boards* event types in regular game play between the 2003-04 and 2016-17 seasons.
22) There will be no difference in the frequency in any MPS level of *head-to-ice* event types in regular game play between the 2003-04 and 2016-17 seasons.

23) There will be no difference in the frequency in any MPS level of *head-to-head* event types in regular game play between the 2003-04 and 2016-17 seasons.
24) There will be no difference in the frequency in any MPS level of *shoulder-to-head* event types in regular game play between the 2003-04 and 2016-17 seasons.
25) There will be no difference in the frequency in any MPS level of *elbow-to-head* event types in regular game play between the 2003-04 and 2016-17 seasons.
26) There will be no difference in the frequency in any MPS level of *glove-to-head* event types in regular game play between the 2003-04 and 2016-17 seasons.
27) There will be no difference in the frequency in any MPS level of *punch (during regular game time)* event types in regular game play between the 2003-04 and 2016-17 seasons.

1.8 Limitations

1) There are limitations when using video analysis, as not all head impact events are recorded. As the wide angle and view of the ice hockey game is meant to capture a majority of the field of play (ice surface) while following the puck, exact location and elevation of head impacts may be difficult to determine. As well, quality of the 2003-04 NHL season game video presented difficulties in identifying head impact events. Therefore, total confirmed head impact frequency is conservative.
2) The Hybrid III head form utilized in this study's head impact evaluations is closely related to adult male head geometry and mass, however, it is not truly biofidelic. The head form is composed of aluminum (skull cap) and rubber ("skin" material) which does not represent the true compliant disposition of human tissue (Hubbard & McLeod, 1974; Seeman, Muzy & Lustick, 1986). The use of cadavers brings with it the difficulty of

tissue preservation and has been shown to result in inconsistent responses (van Dommelen et al., 2009).

3) The ice hockey helmets used in this study was limited to one type of helmet liner (vinyl nitrile) and one shell liner that was most commonly used in both seasons of professional ice hockey. Post and colleagues (2014) demonstrated different that different ice hockey helmets, of varying liner thickness, influence the dynamic head response from shoulder impacts, resulting in MPS values in the very high category, with values of 40.8-50.9% MPS. As not every ice hockey player uses the same type of helmet as other players, the results from this study cannot be generalized to other brands or shell geometry of helmets other than the one used in this study.
4) The UCDBTM Version 2 (V2) used in the Finite Element modelling to determine brain tissue strain from head impact has been validated against post-mortem human subjects research (Hardy et al., 2001). Responses in the model may not be true to living brain tissue under the same dynamic head impact.

1.9 Delimitations

1) Only men's NHL regular season games were used to analyze head impact frequency and brain strain levels for the two seasons. The video was obtained from an external, public website. Any head impacts occurring before and/or after regular game time were excluded from the study as they do not represent head impacts during regular game play.
2) In one regular season of men's professional ice hockey, there are 1,312 games with each team playing 82 games. The velocities and locations of head impact events logged from NHL games used in this study were observed from a small sample of head impact events

from twenty (20) games in each season and may not represent every possible head impact scenario that may have occurred throughout the entire season of professional ice hockey.

3) Fights occurring in the NHL have been reported to be more common in pre-season games compared to regular season or post-season games, with an average of 61.63 fights in the pre-season and 37.62 and 10.14 fights in the regular and post-season, respectively, over ten seasons of professional ice hockey from 2000 to 2011, excluding the 2004-05 season due to the lockout (Goldschmied & Espindola, 2013). In addition to the difficulty in identifying and categorizing head contact from fighting visibility and occurrence, this thesis included fight event frequency during regular season games during regulation time, but frequency-magnitude was not included. Events that include a single punch during regulation time that resulted in contact with an opponent's head was evaluated through frequency and frequency-magnitude.
4) Goalie head impacts was identified in this thesis; however, due to the unique geometry of the helmets, goalie head impact frequency and frequency-magnitude are not be included in this study (Clark et al., 2018).
5) There are several different brain injury (finite element) models used in research that vary in calculating brain strain depending on the model and metric used (Fahlstedt et al., 2020). Due to the continuing reference dataset available in the Neurotrauma Impact Science Laboratory (NISL) at the University of Ottawa, the UCDBTM V2.0 was used in this thesis.

1.10 Significance

Ice hockey is played by over 1.78 million people and enjoyed by countless more (IIHF, 2018). NHL is the highest level of professional ice hockey in North America and is televised by media coverage. Head impacts can result in various levels of brain trauma. Maximum principal strain values as low as 14% have been reported to have a 50% risk of concussion (Kleiven, 2006; Rousseau, 2014). Over the past two decades of ice hockey, several rules have been changed to the game, in the name of both safety and attractiveness (Marek, 2015; Donaldson, Asbridge, & Cusimano, 2013; National Hockey League Official Rules 2010-11, 2010; National Hockey League Official Rules 2011–12, 2011). There continue to be a paucity of research on the effect of these rule changes on head impacts and brain trauma. Using concussion reporting as a measure of brain trauma may not be reliable due to underreporting and difficulty in identifying and diagnosing (Karton et al., 2021; Williamson & Goodman, 2006; McCrea et al., 2004; Goldschmied & Espindola, 2013). As of 2019, there have been twelve reported cases of chronic traumatic encephalopathy (CTE), or brain degeneration, in retired, deceased NHL players (Westhead, 2019). It is unknown if current ice hockey players are experiencing the same level of brain trauma as players in 2003.

This study aims to describe differences in head impact frequency and frequency-magnitude for several head impact events during game play between the 2003 and 2016 NHL seasons to understand rule changes influence on brain trauma and therefore effectiveness in protecting players.

CHAPTER 2: LITERATURE REVIEW

2.1 Mechanism of Head Injury

Head impacts often have lasting effects on the human brain function, altering structural, functional, and metabolic characteristics of the brain (McAllister & McCrea, 2017; Sollmann et al., 2018). Research by Gennarelli and colleagues (1979; 1982) investigated different TBI lesions using cadaver and animal models. Brain injury severity depends on the amount of damaged neural tissue and the magnitude of strain (Nahum & Smith, 1976), where greater forces may generate higher tissue damage. Brain injuries can be classified as either focal or diffuse injuries.

2.1.1 Focal Brain Injury

Focal brain injuries are a result of collision forces acting on the skull resulting in sub-cranial tissue compression at the site of impact (coup injury) or at the site opposing the impact (contre-coup injury) (Andriessen, Jacobs & Vos, 2010; Gurdjian et al., 1968). Examples of focal brain injuries include haematomas and haemorrhagic contusions which are classified as TBI's and represent a more severe injury. These injuries are large enough to be observed using imaging devices, therefore making diagnosis and treatment a more "straight-forward" process. Focal injuries in helmeted sports have occurred less frequently as helmets have been shown to help protect the skull and brain tissues from trauma (Newman, 2005).

2.1.2 Diffuse Brain Injury

Direct and indirect head impacts have the ability to result in brain injury (Viano et al., 1989), where both of these scenarios can cause high linear and/or rotational acceleration that dictates brain injury severity. Diffuse brain injuries result from the main injury mechanism of rotation causing shear and tensile forces within the brain and sub-cranial tissue (Andriessen, Jacobs & Vos, 2010), and affect a diffuse volume of brain tissue. Examples of diffuse brain injuries include diffuse axonal injury (DAI), diffuse vascular injury, hypoxic-ischemic injury, and brain swelling (oedema), where DAI is a different form of TBI due to the extensive shearing of neural tissue involved (Hoshizaki & Brien, 2004). Mild traumatic brain injuries, commonly referred to as concussion, represent a less severe form of diffuse brain injury representing metabolic crisis (Biasca & Simmen, 2004; Giza & Hovda, 2001). While focal injuries are visible on medical imaging devices, diffuse injuries are generally only visible microscopically, rarely appearing on conventional medical imaging devices, while diffuse injury is can be obtained via post-mortem dissections and staining techniques. This makes diagnosis and treatment more complicated.

2.2 Incidence of Head Injury in Ice Hockey

Ice hockey is played at high speeds involving a great deal of physical play in an enclosed field of play creating increased exposure to high energy head impacts (Delaney, 2014). Head impacts result from falls, collisions, projectiles, and punches (Hoshizaki et al., 2013). The most common event resulting in brain trauma in professional ice hockey has been reported to be shoulder collisions (Hutchison, 2011; Post et al., 2019). McKay and colleagues (2013) analyzed six seasons of all NHL games, examining reported injury and illness incidence. An overall average of 5676 injuries during regular season games was reported, with the head being described as the most commonly injured body region (McKay et al., 2013).

Concussion reporting as a measure of brain trauma is not a reliable measure because concussions may be difficult to diagnose due to wide range of physical symptoms and severity, may not be reported in earlier seasons, and have been shown to be underreported (Karton et al., 2021; Williamson & Goodman, 2006; McCrea et al., 2004; Goldschmied & Espindola, 2013). There continues to be no single definition of concussion that is universally accepted; however, the International Conference on Concussion in Sport has kept a similar definition of concussion over the past five conferences (Aubry et al., 2002; McCrory et al., 2013; 2017). Historically, concussions were defined by loss of consciousness (LOC) due to head impact (Ward, 1996; Walker, 1973; Ommaya & Gennarelli, 1974) and when the general definition evolved to include a wider range of signs and symptoms, LOC was a level of severity of concussion (Cantu, 2001). Concussions in sport are reported using subjective, symptom-based diagnostic tools which are not designed to capture the full range of cellular responses associated with brain trauma, making objective measures, such as head impact frequency and maximum principal strain (MPS), better predictors of brain trauma. Magnitude alone does not capture a full profile on brain injury or long-term consequences of repetitive brain strain, as repetitive lower magnitude brain strains have been shown to have similar pathologic outcomes as one severe event (Kondo et al., 2015). Brain trauma profiling has been utilized to capture the spectrum of exposure by determining magnitude of brain strain and frequencies of head impacts.

Neurodegenerative disease, specifically CTE, was thought to be a result from head impacts that occurred in the boxing and American football athletes. As of 2019, there have been twelve reported cases of chronic traumatic encephalopathy (CTE), or brain degeneration, in retired, deceased NHL players, with the latest professional athlete retiring from the sport in 2014 (Westhead, 2019). Continued research support of the understanding that repetitive head impacts cause neurological injury risks from cumulative brain trauma, demonstrated through acute and chronic injury in addition to neurologic disease and mental health disorders among contact sport participants (Montenigro et al., 2017; Guskiewicz et al., 2004; McAllister et al., 2014; Kuzminski et al., 2018). A number of studies provide evidence that repetitive low velocity head impacts have an association with CTE with similar outcomes to one severe head impact event (Kondo et al., 2015; Karton & Hoshizaki, 2018; Bahrami et al., 2016).

2.3 Injury Metrics

2.3.1 Dynamic Head Response

The dynamic head response represents measures of linear and rotational accelerations the head/head form undergo during a head impact. Linear accelerations have been shown to result in focal injuries (Holbourn, 1943; Ommaya & Hirsch, 1971; King et al., 2003; Gennarelli, Thibault & Ommaya, 1972), and have been less common in helmeted sports (Newman, 2005). Rotational accelerations result in shear strains leading to axonal damage seen in diffuse brain injuries (Holbourn, 1943).

2.3.1.1. Linear Acceleration

Linear acceleration of the head has been shown to be associated with increased intracranial pressure gradients (Gurdjian, 1975; Holbourn, 1943), with high peak linear accelerations being shown to associate with the risk of focal injuries and TBI such as subdural haematomas and skull fracture (Holbourn, 1943; Ommaya & Hirsch, 1971; King et al., 2003; Gennarelli, Thibault & Ommaya, 1972; Hoshizaki & Brien, 2004). Studies have reported these increases in intracranial pressure have the ability to create shear stresses in the brain tissue through cadaver specimens (Gurdjian et al., 1961; 1966).

Zhang and colleagues (2004) investigated injury risk thresholds in American football and determined the 25%, 50% and 80% probability of sustaining a concussion (MPS value of 19-30%) were estimated to be at peak linear accelerations of 66 g, 82 g and 106 g, respectively. Several studies have reported that linear acceleration has little effect on injury mechanisms when investigating if a relationship existed between rotational acceleration and both focal and diffuse brain injury (Holbourn, 1943; Gennarelli, Thibault & Ommaya, 1972; Gennarelli, Abel, Adams & Graham, 1979; Forero Rueda et al., 2011).

2.3.1.2. Rotational Acceleration

Rotational acceleration of the head has been shown to be associated with injurious shear stresses and strains that are seen in diffuse brain injuries such as mTBI or concussion (Holbourn, 1943; Gennarelli et al., 1982; Kimpara & Iwamoto, 2011; King et al., 2003; Post et al., 2013c). Research by Gennarelli and colleagues (1982) demonstrated a wide range of brain injuries in animal models that were a result of applied rotational head accelerations. Zhang and colleagues (2004) reported risk of sustaining a concussion (MPS value of 19-30%) at 25%, 50% and 80% probability to have peak rotational accelerations of 4600 rad/s^2, 5900 rad/s^2 and 7900 rad/s^2. Rotational acceleration has been found to have a high correlation with peak strains (Kleiven, 2006). It is unlikely a head impact will produce only linear or rotational acceleration, with research showing injuries are determined by both accelerations combined (Meaney & Smith, 2011).

Protective headgear has been designed to decrease risks of injury by attenuating the forces the head experience and lessen the acceleration of the head during impact. Helmets have been shown to influence the acceleration-time histories generated from head impacts, which has been shown to affect brain strain (Post et al., 2014; Newman, 2005; King et al., 2003; Hoshizaki & Brien, 2004; Holbourn, 1943; Gennarelli et al., 1982).

2.3.2 Frequency

Frequency of head impacts has also been shown to play an influential role on brain injury. Repetitive head impacts resulting in low-magnitude strain of the brain tissues have been shown to result in changes in brain function (McAllister et al., 2014) and structure (Bazarian et al., 2012; Breedlove et al., 2012; Bahrami et al., 2016; Slobounov et al., 2017; Kuzminski et al., 2018; Neselius et al., 2012; Shahim et al., 2017). It is important to note that head impacts not diagnosed as a concussion are events that may reflect lower strain values and still result in negative health effects such as declines in cognitive performance including memory, neurobehavioural changes, functional impairments and neurodegenerative diseases (Hoshizaki et al., 2013; McAllister & McCrea, 2017; Karton & Hoshizaki, 2018; Kondo et al., 2015). Wilcox and colleagues (2014) reported players sustained a total of 1965 and 2532 head impacts on the men's and women's collegiate ice hockey teams, respectively during the 2009-10. Karton and colleagues (2021) examined game video footage in six age divisions of youth minor ice hockey to determine brain trauma exposure. A total of 172 games were reviewed and a total of 1234 head impact events were documented; U11 had the lowest total frequency of head impact events with 145 impacts over 30 games, and U18 had the highest frequency with 317 over 30 games (Karton et al., 2021). Lower-energy magnitudes at higher frequencies may result in long-term neurologic complications. Traditional methods of assessment and diagnostic tools are not sensitive enough to capture these low-magnitude effects on brain trauma.

2.3.3 Magnitude

Head impact magnitude is influenced by the event's specific characteristics of velocity, mass, location and compliance (Oeur et al., 2014; Karton et al., 2014; Oeur & Hoshizaki, 2016). Altering impact characteristics have been shown to change dynamic response curves, creating different levels of brain injury as these characteristics affect how energy moves through the brain (Karton et al., 2014; Post et al., 2013b; Oeur et al., 2014; Kendall et al., 2012). Magnitude of a head impact is typically measured in peak linear and rotational acceleration as both have been linked to brain injury (Gennarelli et al., 1982; Post & Hoshizaki, 2015); however, brain tissue strain has been found to be more closely representative of brain injury (Zhang et al., 2004; Kleiven, 2006; Rousseau, 2014).

Finite element (FE) models of the human brain allow researchers to ethically investigate brain injury from head impacts (Trotta et al., 2020). These models can provide quantitative data on the stress and strain the brain experiences during an impact (Yang & King, 2011). Brain tissue deformation measurements are a better predictor of brain injury than linear or rotational acceleration alone as it has a close association with strain in the brain tissue (King, Yang, Zhang, & Hardy, 2003; Kimpara & Iwamoto, 2011; Post, Hoshizaki, & Gilchrist, 2011; Post & Hoshizaki, 2015). Maximum principal strain (MPS) is the most frequent brain deformation metric used in brain injury prediction and analysis as it has the closest comparison of mechanical failure in anatomical testing (Post & Hoshizaki, 2012; Hoshizaki et al., 2014; McAllister et al., 2012). MPS has been used to measure the elongation of brain tissue along one of the principal axes relative to its original length from head impact (Zhang et al. 2004; Kleiven, 2006; Silva, 2006). Figure 1 demonstrates the calculation for MPS.

Figure 1. *MPS calculation.*

$$\varepsilon 1,2=\frac{\varepsilon_x+\varepsilon_y+\varepsilon_z}{3}\pm\frac{\sqrt{2}}{3}\sqrt{\left(\varepsilon_x-\varepsilon_y\right)^2+\left(\varepsilon_y-\varepsilon_z\right)^2+\left(\varepsilon_z-\varepsilon_x\right)^2}$$

Note. εx, εy and εz = strains measured along corresponding axes.

MPS is a useful metric in injury biomechanics through FE analysis as it has described how trauma and tissue strains are associated with injury severity. MPS values have been categorized into levels of brain strain (Table 8, Section 3.8). As concussion continues to be a cause for concern in the sporting world, though it possesses intrinsic difficulty in recognition and diagnosis, research has continued to revolve around concussion reporting and has found that 50%

probability of sustaining concussion in sport occurs at maximum principal strain (MPS) values of 19-30%, with values as low as 5-15% having been shown to cause functional impairments in neuronal signal transmission (Margulies & Thibault, 1992; Bain & Meaney, 2000; Singh et al., 2006; Elkin & Morrison, 2007). The minimum level of injury required to induce calcium influx was reported by Yuen and colleagues (2009) using cellular cultures to be 5% strain. Brain injury may also occur at lower levels of strain that do not elicit symptoms normally associated with concussions. Cournoyer (2019) investigated MPS levels associated with loss of consciousness from head impact in professional American football, with results demonstrating MPS levels as low as 31% strain in the thalamus and as high as 54% strain in the cerebral cortex. Laboratory reconstructions of professional ice hockey head impacts carried out by Post and colleagues (2019) produced MPS values as high as 48% in head-to-ice impact events, and MPS values as low as 21.3% in puck-to-head impact events. Repetitive lower strain impacts may be associated with neurological degenerative diseases such as chronic traumatic encephalopathy (CTE), affecting athletes long after retirement (McKee et al., 2010).

2.4 Head Impact Characteristics

Differences in impact characteristics create dynamic head responses that lead to various levels of brain trauma (Hoshizaki et al., 2013). Impact characteristics of velocity, location, mass, and compliance contribute to the dynamic head response and strain magnitude (Gennarelli et al., 1982; Gennarelli et al., 1987; Zhang et al., 2001; Hoshizaki et al., 2014; Oeur et al., 2014). In ice hockey, the head can be impacted in various ways through different mechanisms, with each impact comprised of unique variations of the impact characteristics, creating different injury levels via strain placed on neural tissues.

2.4.1 Impact Velocity

Velocity at impact, or inbound velocity, has been reported to influence head dynamic response during impacts. Research by Post and colleagues (2013b) investigated the influence of velocity on peak brain strain magnitudes in American football. With a pneumatic linear impactor, a Hybrid III head form was impacted at centric and non-centric locations, at velocities of 5.5 m/s, 7.5 m/s, and 9.5 m/s consistent with velocities encountered by American football players during collisions. Velocities of 5.5 and 7.5 m/s had similar brain deformation values (MPS) with velocity at 9.5 m/s producing higher rotational acceleration and brain deformation (Post et al., 2013b). Rousseau (2014) analyzed the velocities of concussive and non-concussive impacts of shoulder and elbow events in professional ice hockey. Velocities that resulted in concussion ranged from 4.1 to 9.0 m/s (mean: 6.0 m/s) and produced an average 0.24 ± 0.09 MPS, and velocities that resulted in no injury ranged from 3.2 to 8.6 m/s (mean: 5.8 m/s) and produced an average 0.22 ± 0.07 MPS. Oeur (2018) investigated the influence of impact characteristics on brain trauma and determined impact velocity had the most influence on strain with velocities of 1.5, 3.0, 4.5 and 6.0 m/s tested. The results from Post and colleagues (2013b), Rousseau (2014) and Oeur (2018) suggest changes in impact velocities influence brain strain magnitudes.

2.4.2 Impact Location

Impact location has been reported to influence brain strain magnitude using cadaver and animal models (Hodgson, Thomas & Khalil, 1983; Gennarelli et al., 1982; Gennarelli et al., 1987), as well as anthropometric dummies and finite element modelling (Mihalik et al., 2012; Tiernan & Byrne, 2019; Walsh, Rousseau & Hoshizaki, 2011; Zhang et al., 2001). Impacts to the side of the head have been shown to produce higher dynamic head responses compared to other impact locations (Mihalik et al., 2012; Hodgson, Thomas & Khalil, 1983). Impacts to the head in a centric (centre of gravity) or non-centric (not through centre of gravity; above, below) have also been reported in the literature to influence head dynamic response (Post, Hoshizaki, & Gilchrist, 2011; Walsh, Rousseau & Hoshizaki, 2011; Clark et al, 2016; Karton et al., 2014). Research by Walsh and colleagues (2011) has shown non-centric impacts at the rear boss location with a -45° rotation in the transverse plane produce higher peak rotational accelerations compared to centric impacts at the same location and have a higher probability of sustaining brain injury.

2.4.3 Effective Mass

Research has shown that an increase in mass results in an increase in the dynamic head response (Karton et al., 2014). When compared to inbound velocity and impact location, effective mass has less influence on the dynamic head response (Karton et al., 2014; Oeur et al., 2019; Meliambro et al., 2022). Karton and colleagues (2014) investigated the effects of various inbound masses on dynamic head response and brain tissue deformation. Using a pendulum impactor with a range of masses that were described in various sport impacts (4.3 kg; 6.3 kg; 8.3 kg; 10.3 kg; 12.3 kg; 14.3 kg), a Hybrid III head form was impacted at various locations under centric and non-centric conditions at a velocity of 4.0 m/s. The results demonstrated that as inbound mass increased, peak linear accelerations also increased, while peak rotational accelerations and brain tissue deformations (peak maximum principal strain; von Mises stress) were more variable and dependent on location of the impact (Karton et al., 2014). These results demonstrate effective mass is an important characteristic to consider when performing head impact evaluations and assessing brain trauma (Karton et al., 2014).

2.4.4 Impact Compliance

In ice hockey there are a variety of impact surfaces that represent a range of compliances that a helmeted head could impact. Impact compliance is defined by stiffness of the materials of the impact event in which the rate of energy transferred to the head directly affects the magnitude and duration of the impact. Impact events such as shoulder-to-head and glove-to-head are described as high compliance events, which result in lower magnitude accelerations and brain strain and increasing the duration to approximately 30 ms (Gurdjian et al., 1964; Hoshizaki & Brien, 2004; de Grau et al., 2020; Kleiven, 2006; Gilchrist, 2003). Impact events such as head-to-ice and head-to-boards are described as low compliance events, which result in high magnitude accelerations with duration over approximately 5 ms (Doorly et al., 2005; Oeur et al., 2015; Post et al., 2014). Longer-duration impact has been shown to increase brain injury through high magnitude strains due to the viscoelastic properties of brain tissue (Post et al., 2014; Rousseau, 2014).

2.5 Rule Changes in Sport

In attempt to reduce the incidences of injury, game rules have been implemented and changed in a variety of sports, including American football (Stemper et al., 2019), rugby (Hendricks, Lambert, Brown, Readhead, & Viljoen, 2014), cheerleading (Yau et al., 2019) and ice hockey (Donaldson, Asbridge, & Cusimano, 2013).

In American professional football, changes to game rules intended to eliminate helmet-to-helmet contact with defenseless players in 2010 and changes to lines of play during free kicks/kickoffs in 2011 have been reported to decrease head injury occurrence (Ruestow, Duke, Finley, & Pierce, 2015). In professional male soccer, a stricter penalization (red card) implemented in 2006 for intentional elbow-to-head contact has reported a 29% decrease of head injuries, with a reduction of concussion by 29%, encompassing thirteen seasons (Beaudouin, Aus der Fünten, Tröß, Reinsberger, & Meyer, 2019). The 2006 elimination of the basket-toss stunt on hard surfaces, specifically basketball courts, in American high school and collegiate cheerleading had led to a reported overall injury reduction of 74% since the year after the rule change, where the authors also reported the most common injury was sustained to the head from the basket-toss at 47% (Yau et al., 2019).

2.5.1 Rule Changes in Ice Hockey

A rule for zero-tolerance for head contact was implemented in 2011 for all youth ice hockey in Canada. Krolikowski and colleagues (2016) reported an increase risk of game-related concussions, an increased risk of more severe concussions, and an increase rate of concussions due to the introduction of body checking and direct head contact in both Peewee and Bantam age groups from 2007-08 (Peewee, U13) and 2008-09 (Bantam, U15) to 2011-12; body checking was the concussion mechanism that had the highest number of concussions. The authors reported concussion incidence rate ratios (IRR) per 1000 game-exposure hours of 1.96 and 2.65 for Peewee and Bantam, respectively, and more severe concussion IRRs (per 1000 game-exposure hours) of 4.12 and 7.91 for Peewee and Bantam, respectively; a more severe concussion was defined by the authors as >10 days of time loss following the injury. It was noted that the increase of direct head contact could have been due to a heightened awareness and increased reporting of hits to the head, as well as more conservative return-to-play injury management (Krolikowski et al., 2016). Concussion reporting is utilized by a number of studies; however, is based on individualized outcomes of signs and symptoms and does not appropriately represent the physical injury the brain undergoes. Research by Karton and colleagues (2021) and Chen (2018) reported frequency and magnitude of head impacts in youth ice hockey age groups that included body checking being introduced in the U15 age group. Both authors reported U15 ice hockey players had experienced higher frequencies of head impacts compared to younger age groups where body checking was not allowed. Karton and colleagues (2021) reported an increase in frequency of higher than 0.17 strain at U15, while Chen (2018) reported U15 experienced higher frequencies of head impacts that resulted in 0.08 to 0.26 strain, which correlates to the majority of the range of brain strain that results in concussion. It was also reported by Karton and colleagues (2021) that U18 ice hockey players experienced a higher total frequency of head impacts than U15, with 10.57 head impact events per game.

In the National Hockey League (NHL), the organization for North American professional ice hockey teams, there has been several rule changes to the game during the past two decades, as summarized in Table 1 (Marek, 2015; Donaldson, Asbridge, & Cusimano, 2013; National Hockey League Official Rules 2010–11, 2010; National Hockey League Official Rules 2011–12, 2011). Marek (2015) described two main reasons for rule changes in ice hockey: safety of players and spectators, and attractiveness of matches. As a result, from the 2005 Lockout in NHL, a group of rules were added and/or modified: redefining lines on the ice (neutral zone reduced, goal line moved closed to the end of the boards, new trapezoid-shaped area behind net), changes to goaltender equipment, “icing” substitution rules, shootout rules, penalties for fighting, and the removal of the 2-Line Pass Rule (Marek, 2015). In 2010, the NHL introduced Rule 48 which made targeting an opponent’s head from the blind side illegal (Donaldson, Asbridge, & Cusimano, 2013; National Hockey League Official Rules 2010–11, 2010). This rule was modified in 2011-12 to encompass all hits to the head (Donaldson, Asbridge, & Cusimano, 2013; National Hockey League Official Rules 2011–12, 2011).

Table 1. *Rule changes since 1992 in the National Hockey League (NHL).*

Year	Rule change(s)
1992-93	Stricter penalty added for instigating fight
2003-04	Changes to maximum length of goaltender pads
2004-05	***NHL Lockout***
2005-06	Changes to neutral zone size* Elimination of red line (removal of 2-Line Pass Rule)* Stricter fighting penalties* Changes to goaltender area of play behind net Changes to goaltender equipment
2010-11	Changes to goaltender equipment Rule 48 (blindside head contact)*
2011-12	Rule 48 modification (include all head contact illegal)*
2013-14	Changes to goaltender equipment
2014-15	More penalties for fighting* Penalty for grabbing face mask*
2015-16	Regular-season overtime players on ice reduced
2019-20	Stricter helmet-wearing rules

Note. * denotes rule changes that directly include lines on the field of play on ice, head contact, and fighting.
Note. (Marek, 2015; Donaldson et al., 2013; National Hockey League Official Rules 2010-11, 2010; 2011-12, 2011; 2014-15, 2014; "Historical Rule Changes", n.d.).

A study by Donaldson and colleagues (2013) investigated the number of concussions and suspected concussions in seasons before, during, and after Rule 48, with reported incidences of concussions of 3.58, 5.28, and 6.83 per 100 games in 2009-10, 2010-11, and 2011-12 regular season NHL games, respectively. Reported concussions did not decrease following the modification of Rule 48. The authors noted that "penalization of intentional checking to the head may not be effective on its own as a strategy to reduce concussion incidence", and enforcement needs to be addressed or other changes need to be introduced to help decrease the risk of concussions (Donaldson, Asbridge, & Cusimano, 2013).

Changes to the field of play have the ability to influence how and where players move, which in turn can influence player-to-player and player-to-object contact, and therefore, brain trauma from head impact. Penalizing the targeting of an opponent's head (Rule 48) should decrease the frequency of head impacts. Nevertheless, despite the adoption of recent rule changes, the risks for potential brain trauma still remains high in professional ice hockey. Measuring frequency of head impacts and magnitude of brain strain will allow the understanding of how rule changes have affected overall brain trauma.

CHAPTER 3: METHODOLOGY

3.1 Overview

Video footage of NHL regular season games during the 2003-04 and 2016-17 seasons were collected from a public source website (Youtube.ca). Head impact events were classified as confirmed or suspected using inclusion/exclusion criteria. All confirmed head impact events were logged and clipped using the video capture software, WM Capture (San Anselmo, CA). Frequency of head impacts was determined per game. Inbound velocity was determined using Kinovea software (0.8.20, open source, kinovea.org). Reconstructions were conducted on confirmed head impacts with each impacts' characteristics (velocity, location, elevation, event type). Head impact kinematic data was collected from the reconstructions and inputted into an FE model to determine MPS values and further categorized into MPS level categories.

3.2 Video Collection

3.2.1 Inclusion/Exclusion Criteria

Video footage of twenty 2003-04 and twenty 2016-17 men's professional ice hockey games were included in this study. Only games during the regular season in each respective season were included; "pre-season", "play-off" or "final competition" games were not included. Each game was reviewed twice by two separate researchers. Observed head impact events from the video footage were logged as either confirmed head impacts or suspected head impacts. All head impact events logged by the initial two researchers were collated by an experienced third reviewer to confirm all head impacts met the inclusion criteria and any duplicates of impact events were excluded.

The inclusion criteria for confirmed head impacts was defined as having both the impact event type and contact with the head itself clearly visible in the video. Suspected head impacts were defined as the head contact not being clearly visible in the video but suspected by the researcher due to the events of play leading to the impact. Suspected head impacts were not included in this study because the head impact was not clearly visible, where the point of contact was obstructed in some capacity, and therefore could not be qualified nor quantified (Chen, 2018; Post et al., 2020). Head impacts that occurred during regular game time in regular season games were included in this study; any head impacts that occurred outside of regular gameplay (i.e., during warm-up, after any referee whistle denoting stoppage in gameplay, end of the third period denoting overtime) were excluded from this study.

3.2.2 Data Collection

The forty games (twenty of each season; 2003-04 and 2016-17) were obtained through the website Youtube.ca. The open-access video capture software, WM Capture 8 (San Anselmo, CA), was used to record the footage from the website. When a head impact event was identified, the video was clipped using WM Capture 8 at 25 frames per second and the description including time stamp of the event was logged in an excel file. Each head impact was categorized into one of the following event types: glass, boards, ice, head, shoulder, elbow, glove, punch, fight, scrum, puck, stick, or other. Glass, boards, ice, head, shoulder, elbow, glove and puck impact events were defined as the head impacting or being impacted by the respective object or body segment. Fighting events were classified into one of the following groups: fight, scrum, or punch. A fight was defined as multiple punches/hits to the head with a closed fist where a players’ gloves were or were not removed and a major penalty for fighting was given to player(s). A scrum was defined as an event when players’ gloves stay on, players’ bodies come together with possible intent to begin a fight but no punches/hits to the head were observed. A punch was defined as an intentional, single hit to a player’s head with an opponent’s closed fist.

Punch events were further described as ‘during regular gameplay’ or ‘outside regular gameplay’, with outside denoting a punch observed after the stoppage of gameplay by a referee. Average player age, weight, and height in the 2003-04 and 2016-17 NHL seasons are described in Table 2.

Table 2. *Average age, in years, average weight, in kilograms, average height, in metres, of players in the 2003-04 and 2016-17 NHL seasons.*

	NHL season	
	2003-04	*2016-17*
Avg age (years)	27.5	27.3
Avg weight (kg)	93.6	91.5
Avg height (m)	1.86	1.86

Note. (“NHL stats”, n.d.)

3.3 Head Impact Event Identification

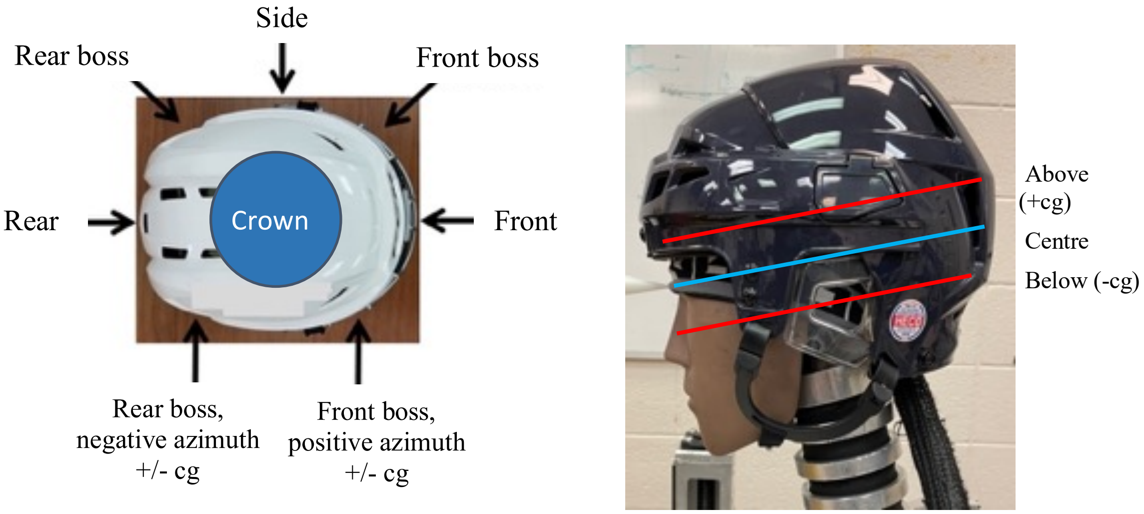
3.3.1 Impact Event Type

The head impact events were categorized within the following event types representing distinct mechanisms of head contact: 1) *Head-to-Glass*; 2) *Head-to-Boards*; 3) *Head-to-ice*; 4) *Head-to-Head*; 5) *Shoulder-to-Head*; 6) *Elbow-to-head*; 7) *Glove-to-head*; 8) *Punch*; 9) *Puck*; 10) *Stick*; and 11) *Other*. Events categorized as *‘Other’* included head contact occurring with body segments not previously mentioned such as knee, hip, or chest, as well as stick-to-head events. For the scope of this thesis, ‘*Puck*’, ‘*Stick*’ and ‘*Other*’ impact events were excluded from laboratory head impact evaluations; however, these events were included for head impact frequency analyses.

3.3.2 Impact Location and Elevation

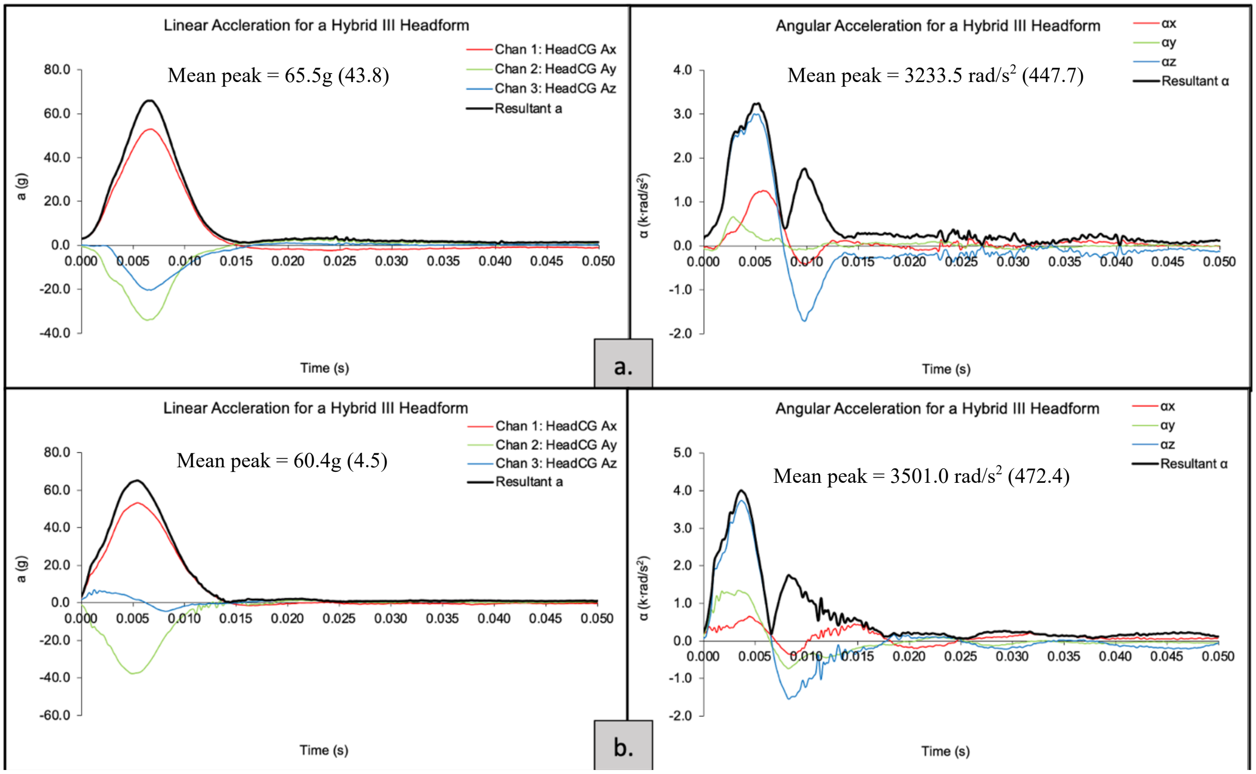
The head impact location categories used in this study were adapted from previous hockey-related video analysis research (Post et al., 2019; Rousseau, 2014; Hutchison, 2011; Kendall, 2016). Head impact location categories included: 1) *Front*; 2) *Front Boss*; 3) *Side*; 4) *Rear Boss*; 5) *Rear*; and, 6) *Crown*. These impact locations divided the head into eight, equal 45° regions of the head in the transverse plane, in addition to the ‘Crown’ region located at the top of the head along the vertical axis (Figure 2). To provide a feasible number of reconstructions in addition to these elevations capturing most of the variance in MPS (Walsh & Hoshizaki, 2012), an impact elevation system that described three elevations (above, centre, below) in terms of centre of gravity (cg) in the sagittal plane were used (Figure 2). Above and below cg elevations were located one inch above and below the centre of gravity of the head in head impact evaluations that employed the pneumatic linear impactor and pendulum impactor as these elevations were able to be measured more precisely. Due to limitation of the equipment, head impact reconstructions (head-to-glass, -boards, -ice) that employed the monorail drop rig at elevations above and below cg were measured at two inches above and below centre of gravity. For impacts at the front boss location with elevation above or below centre of gravity and for impacts at the rear boss location with elevation above or below centre of gravity, a 45° positive and negative azimuth, respectively, was applied for reconstructions as they were observed to be the most common direction of impact (Karton et al., 2021).

Figure 2. *Location (left) and elevation (right) of head impact.*



To assist with feasibility of this thesis, rear and rear boss locations were reconstructed once for both seasons if multiple head impacts of identical velocity, location, elevation and event type were observed from video analysis. To establish if visor and no-visor conditions produced a similar head response, two reconstructions, one with a visor attached to the helmet and one with no visor attached, was completed using a flat modular elastomer programmer (MEP) anvil to represent ice surface at the rear boss location at a velocity of 3 m/s (median velocity of the low velocity bin). MEP was used to best represent ice compliance (CSA Z262.1-15), and the rear boss location was used because it has the most geometry on the helmet, creating a source of variance in response. The mass of the helmet with the visor was 0.693 kg, compared to the mass of the helmet with no visor was 0.565 kg. These two reconstructions resulted in similar head dynamic response curves (Figure 3).

Figure 3. *Linear and rotational (angular) acceleration curves of helmeted head impact using an MEP anvil at the rear boss location and centre of gravity elevation, with no visor (a) and with visor (b).*



3.3.3 Impact Velocity

All head impact events were grouped into the following defined impact velocity categories: *Very low* (0-1.99 m/s); *Low* (2-3.99 m/s); *Medium* (4-5.99 m/s); *High* (6-7.99 m/s); and, *Very high* (≥8 m/s).

During the initial video review, head impact events were logged by researchers as *estimated velocity* categories. Estimated head impact velocities that met the inclusion/exclusion criteria (outlined in Section 3.4.2) were then placed into *calculated velocity* categories with velocities determined using Kinovea video analysis (described in Section 3.4.3).

3.4 Video Analysis

3.4.1 Kinovea

Video analysis techniques have been commonly used in previous head biomechanical research in sports-related settings such as ice hockey, football, and rugby (Rousseau & Hoshizaki, 2015; Post et al., 2014; Karton, 2019; Reardon, Tobin, Tierney & Delahunt, 2016; Hendricks, Karpul, Nicolls & Lambert, 2012). These techniques have been useful in head impact reconstructions by determining impact location, impact elevation, and inbound velocities. The open-access video analysis software, Kinovea 0.8.20 (open source, Kinovea.org), was used in this thesis to verify impact event types, impact location and impact elevation, in addition to calculating the inbound impact velocities of the impact event.

3.4.2 Inclusion/Exclusion Criteria

Kinovea video analyses were conducted to calculate impact velocities for confirmed head impact events if the following inclusion criteria were met: (1) head impact events must be a single impact to the head; (2) the player’s head must be the initial point of contact; (3) both the head impact and the impact event type must be clearly visible within the video; (4) the dimensions of the ice rink must be known; and, (5) sufficient number of markings on the ice rink must be visible in the camera's view (Chen, 2018; Kosziwka, 2018).

3.4.3 Velocity Calculation

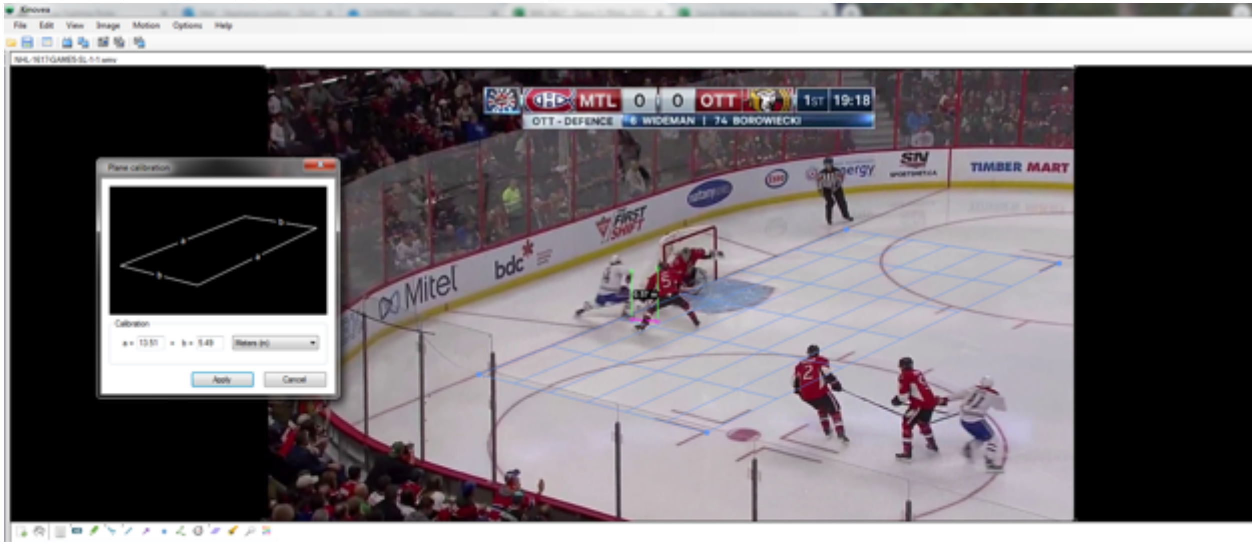
Impact velocities of head impact events that met the inclusion/exclusion criteria (Section 3.4.2) were calculated using the video footage in this study. The video footage was recorded at a frame rate of 25 frames per second. Physical dimensions of the standard NHL ice hockey rink were obtained (Appendix A). Kinovea was used with a perspective grid calibration to scale the video footage to known physical dimensions of the rink, including ice, boards, glass, net and helmet dimensions. The impacting velocities were calculated with the distance and time of each impact (Figure 4). If there were not sufficient ice rink markings available to calculate velocity, *estimated velocities* were used.

Figure 4. *Velocity equation.*

$$\boxed{Velocity = \frac{distance\ travelled}{time\ to\ impact}}$$

For collision-type events (head-to-glass, head-to-boards; shoulder-to-head, elbow-to-head, glove-to-head; puck), the distance between the impacted head and surface/object was calculated using a horizontal perspective grid laid upon the ice surface of the hockey rink at 3-5 frames prior to the moment of impact (t = 0.12-0.2 s) (Figure 5).

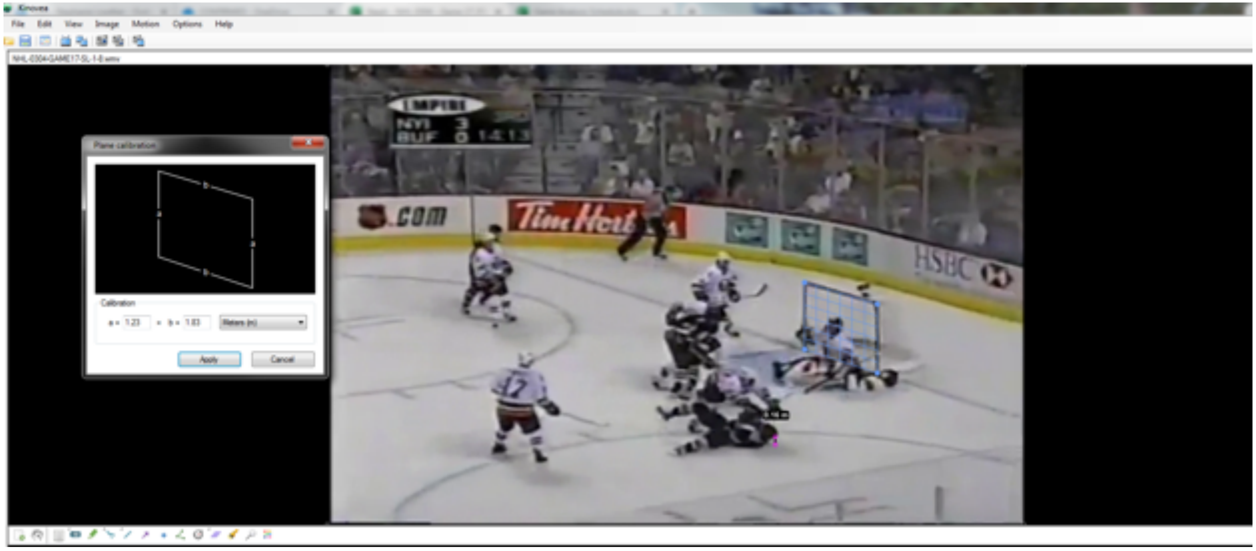
Figure 5. *Perspective grid calibration and distance travelled shown at 5 frames prior to the moment of impact for an elbow-to-head impact event.*



a = 13.51 × b = 5.49 Meters (m)

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

Figure 6. *Perspective grid calibration and distance travelled shown at 1 frame prior to the moment of impact for a head-to-ice impact event.*



a = 1.23 × b = 1.83 Meters (m)

For punch events, the distance between the impacted head and inbound fist was calculated using the dimensions of the helmet (Figure 7) of either player involved (puncher or target) between 2 frames (t = 0.08 s) and 5 frames (t = 0.2 s) prior to the moment of impact (Figure 8).

Figure 7. *Helmet dimensions used for distance to impact.*

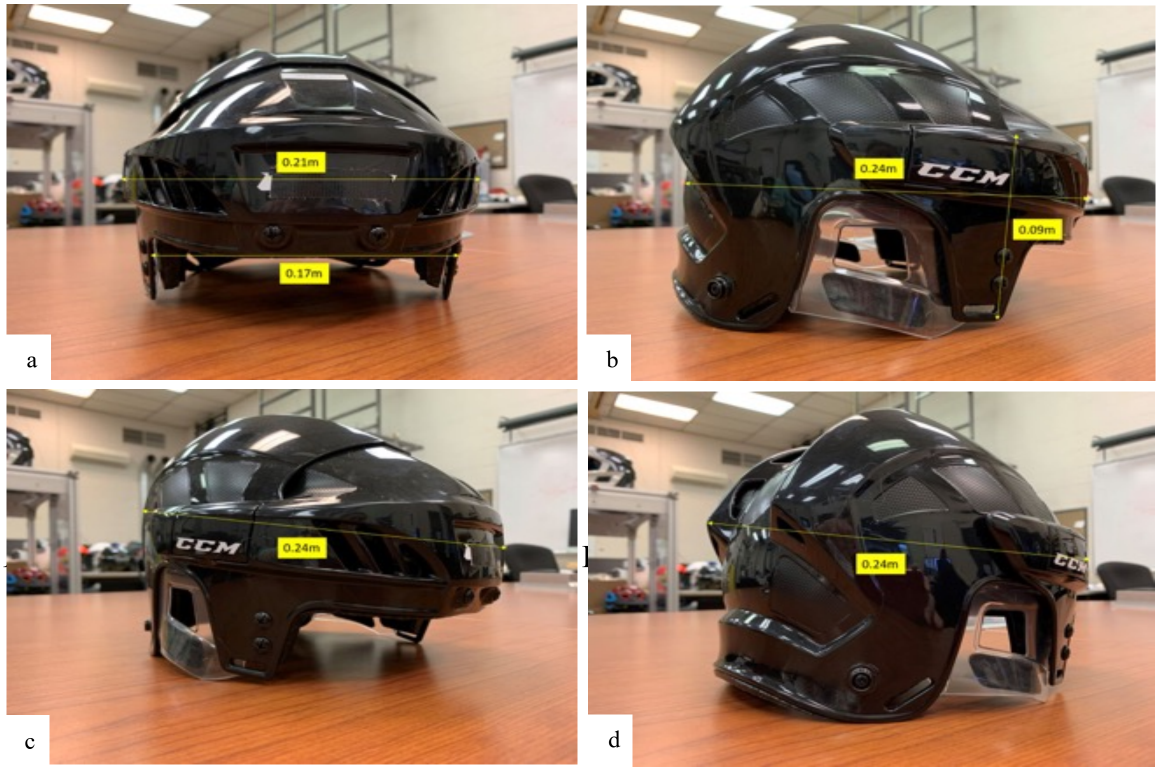
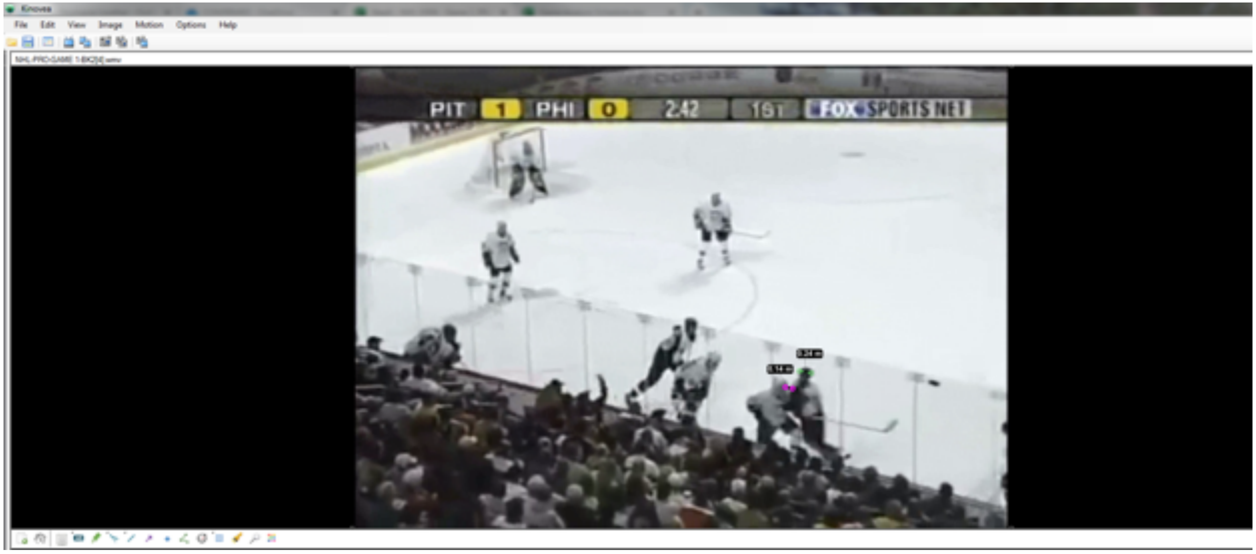


Figure 8. *Perspective grid calibration and distance travelled shown at 2 frames prior to the moment of impact for a punch event.*



Inbound velocities for each head impact event was calculated twice by the same researcher. All confirmed head impact event velocities were calculated using Kinovea for two trials within a 1-week timeframe following the initial review (Trail 1). The final calculated velocity for each impact event was taken as an average of the two velocities determined from Trail 1 and Trail 2. If there was a discrepancy of more than 1 m/s between the two calculated velocities, a third trial was performed by another researcher. This method of calculating velocities with Kinovea has a reported error of less than 20% depending on the angle of view, distance to the camera and speed of skater, determined by Post and colleagues (2018). The categorized Kinovea velocities for each confirmed head impact event are reported in Appendix (Appendix B). Each impact was designated a velocity category based on the following ranges: very low (0-1.99 m/s); low (2-3.99 m/s); medium (4-5.99 m/s); high (6-7.99 m/s); very high (≥8 m/s). The median velocity in each velocity bin will be used for head impact evaluations reconstructed in the laboratory (Table 3).

Table 3. *Median velocities of each velocity bin.*

Velocity Bin	**Very Low** (0-1.99 m/s)	**Low** (2-3.99 m/s)	**Medium** (4-5.99 m/s)	**High** (6-7.99 m/s)	**Very High** (≥8 m/s)
Median Velocity	*1.00 m/s*	*3.00 m/s*	*5.00 m/s*	*7.00 m/s*	*9.00 m/s*

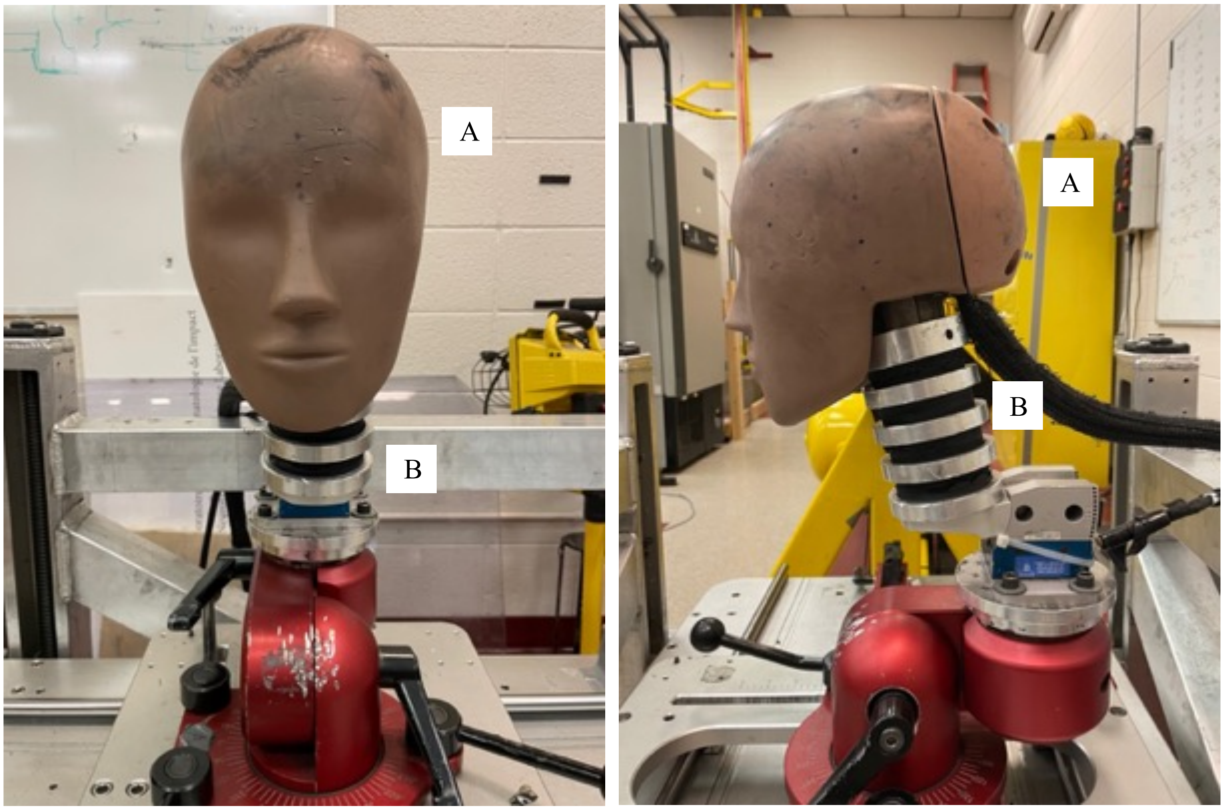
3.5 Equipment

3.5.1 Hybrid III Head Form and Neck form

A male 50th percentile Hybrid III head form (4.54 ± 0.01 kg) was used throughout this thesis as it is based on the average head mass and circumference of male adults. The head form is commonly used in research as it is representative of the human head in laboratory reconstructions (Post & Hoshizaki, 2015; Yoganandan et al., 2009). The head form is comprised of steel interior covered with a vinyl skin (Figure 9), and fitted with nine, single-axis Endevco 7264C-2KTZ-2-300 accelerometers (Endevco, San Juan Capistrano, CA, USA) in an orthogonal “3-2-2-2” array to collect the dynamic head response data, developed by Padgaonkar and colleagues (1975) to collect three-dimensional rotational acceleration during an impact (x-axis: forward/backward; y-axis: left/right; z-axis: up/down). The accelerometer data was sampled at

20 kHz, collected using TDAS Pro Lab System (DTS, Seal Beach, CA, USA), and filtered using the SAE J211 CFC 1000 protocol (1650 Hz low-pass filter).

Figure 9. *Hybrid III head form (*A*) and unbiased neck form (*B*).*



The Hybrid III head form was attached to an unbiased neck form (1.54 ± 0.01 kg) used in all head-to-head, shoulder-to-head, elbow-to-head, glove-to-head, and punch head impact evaluations. Head-to-boards head impact evaluations were reconstructed without the use of the neck form where the head form was placed in a drop carriage attached to the guided rail system that allowed the head to impact the anvil and respond freely post-impact (Figure 10). The unbiased neck form is comprised of aluminum disks, each consisting of uniform radius (85.6 mm) and height (12.8 mm), and unarticulated rubber butyl disks, each consisting uniform radius (68.0 mm) and height (21.5 mm) (Figure 9). This neck form has been used in previous research to remove the neck's bias on rotational impact response for all planes of movement (Walsh et al., 2018).

Figure 10. *Drop carriages used for head-to-boards impact events.*

Note. Drop carriage used for flat boards anvil (A), Drop carriage used for angled (45°) boards anvil (B).

3.5.2 Helmets and Visors

The Hybrid III head form was outfitted with a certified CCM Vector 8 (vinyl nitrile) senior hockey helmet for all laboratory head impact evaluations (Figure 11). A certified CCM visor was equipped to the helmet for laboratory reconstructions representing head impacts from the 2016-17 season (Figure 11A). No visor was equipped to the helmet for reconstructions to represent the 2003-04 season's head impacts (Figure 11B). The helmeted head form was impacted three times per velocity for each unique event type, location, and elevation, with a new helmet used for each velocity. Post and colleagues (2014) examined the efficacy of ten different types of ice hockey helmets in protecting professional ice hockey players for a documented condition where w concussion occurred from a shoulder-to-head impact. The authors' research demonstrated that different ice hockey helmets, each with different liner thicknesses, influence the motion of the head from an impact. To limit the variance due to helmet differences in this study, and due to CCM being the most common brand of helmet used by the professional athletes in both the 2003-04 and 2016-17 seasons, the same type of helmet was used.

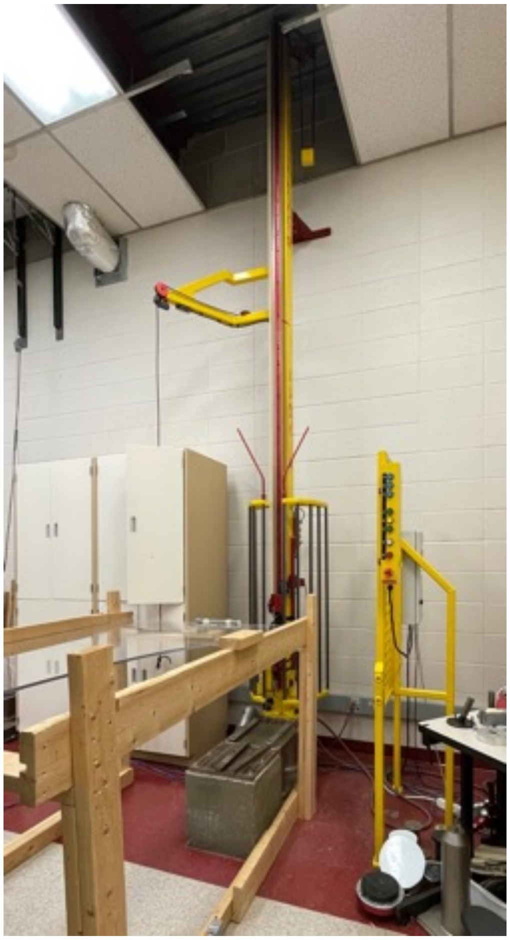
Figure 11. *CCM Vector 8 helmet.*

Note. Helmet with visor (A), Helmet without visor (B).

3.5.3 Monorail Drop Rig

The monorail drop rig is a guided free-fall impacting system, consisting of a vertical rail (4.7 m tall) secured to a wall and a concrete base (Figure 12). The head form was attached to the vertical guided rail system via free-drop or holding carriage (Figure 10). The head form is raised on the vertical rail through the use of a motorized system, with release initiated by a pneumatic piston. The head form impacts an anvil at the base of the vertical rail. Anvils are secured to the floor via a concrete block (board anvils, ice anvil) or wooden frame (glass anvil). Velocity was calculated by a photoelectric time gate positioned above the anvil for each impact.

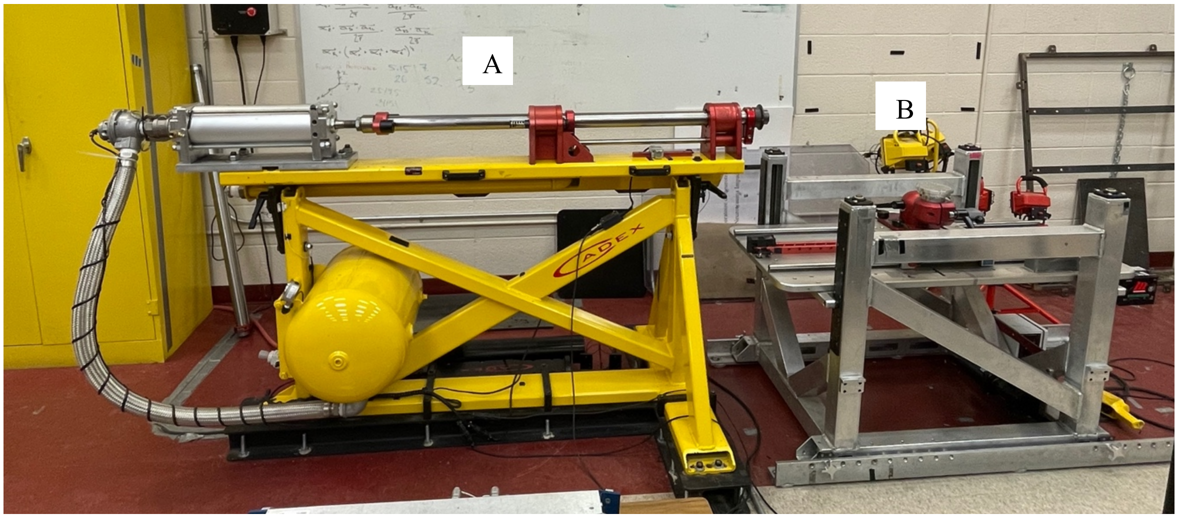
Figure 12. *Monorail drop rig setup for head-to-glass impacts.*



3.5.4 Pneumatic Linear Impactor

The pneumatic linear impactor is composed of a steel frame secured to the floor that supports an impacting arm (13.1 kg), a piston and a pressurized tank (Figure 13). The impacting arm is propelled forward by the piston with pressurized air from the tank, producing the desired velocity. A set velocity (1 m/s; 3 m/s; 5 m/s) was achieved by adjusting the position of the piston arm prior to the pressurized air entering the piston chamber to propel the piston arm and impacting arm forwards. Velocity was measured from a photoelectric time gate positioned 0.254 m from the impacting end of the steel frame. Pressure within the compressed air tank was maintained at 22 Psi to prevent fluctuations in the set velocity(s). The head form was attached to a motorized table (12.78 kg) (Figure 13), sliding on low-friction rails that permit post-impact translation and could be raised or lowered to achieve various elevations (above; centre; below).

Figure 13. *Pneumatic linear impactor.*

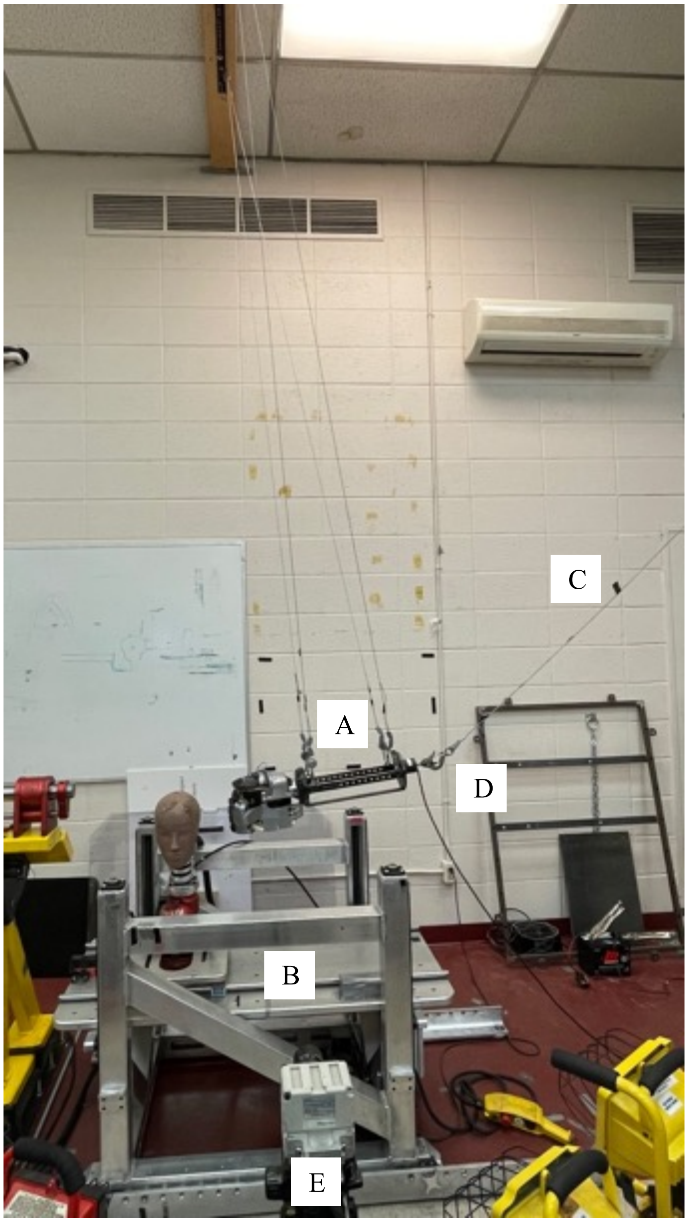


Note. Pneumatic linear impactor (A), Motorized table (B).

3.5.5 Pendulum Impactor

The pendulum impactor is composed of four guide wires suspended above the top of a motorized table (12.78 kg) (Figure 14). A motorized winch system, secured to the wall, had a release mechanism (electromagnet; quick release clip) on the end that was attached to the swinging end of the pendulum and was raised to a predetermined height that produced the targeted inbound velocity (1 m/s; 3 m/s; 5 m/s). Velocity was calculated with the use of a High-Speed Imaging PCI512 camera sampling at 1000 fps. The pendulum was released to allow the impacting condition (elbow; glove; head; punch) to freely impact the helmeted Hybrid III head form attached to the motorized table.

Figure 14. *Pendulum impactor setup for punch impacts.*



Note. Pendulum apparatus (A), Motorized table (B), Winch cable (C), Release mechanism (D), High speed camera (E).

3.6 Head Impact Evaluations

Head impact evaluations employed the monorail drop rig, the pneumatic linear impactor, and the pendulum impactor to represent the various impact events included in this thesis. A summary of equipment and event type can be found in Table 4 and Table 5. The effective mass involved in each event type in this thesis is based on published research and is summarized in Table 6.

Table 4. *Test equipment and anvils for glass, boards and ice impact events*

Event	Glass	Boards	Ice
Equipment[1,2]	Monorail Drop Rig	Monorail Drop Rig	Monorail Drop Rig
Anvil	Polycarbonate glass	Flat and angled steel anvil with high density polyethylene	Frozen ice anvil

Note. [1] Post et al., 2019; [2] Meehan, 2019

Table 5. *Test equipment and anvils for collision-type events*

Event	Head	Shoulder	Elbow	Glove	Punch
Equipment[1-4]	Pendulum	Linear Impactor	Pendulum	Pendulum	Pendulum
Anvil	Helmeted head form	Medium compliance striker cap with shoulder pad	Elbow striker with elbow pad	Impacting anvil with ice hockey glove (skater; goalie)	Impacting anvil with skater ice hockey glove

Note. [1] Post et al., 2019; [2] Post et al., 2020; [3] Meehan, 2019; [4] Rousseau, 2014

Table 6. *Total impacting mass for collision-type events*

Event	Head	Shoulder	Elbow	Glove	Punch
Impact mass, kg[1-6]	4.99	13.1	6.2	0.96 (skater) 1.52 (goalie)	5.23

Note. [1] Post et al., 2019; [2] Post et al., 2020; [3] Meehan, 2019; [4] Rousseau, 2014; [5] Kendall, 2016; [6] Clauser et al., 1969

3.6.1 Head-to-Glass, Head-to-Boards, and Head-to-Ice Impact Events

A monorail drop rig was used to simulate fall (head-to-ice) and collision (head-to-boards, head-to-glass) events and was based on methodology of previous research (Meehan, 2019; Post et al., 2019). For head-to-board events (Figure 15a, 15b), the helmeted Hybrid III head form was positioned on a free-drop carriage, which was raised to and dropped from a predetermined height that produced the targeted inbound velocity (1 m/s; 3 m/s; 5 m/s). The carriage was attached to guided rail system and landed on a braking system that allowed the head form to respond freely post-impact. A steel anvil (flat; angled, 45°) supporting a round piece of high-density polyethylene (0.012 m thick) was used to reconstruct head-to-board impacts. For head-to-ice and head-to-glass events, the helmeted Hybrid III head form and unbiased neck form were attached to a guided rail system via a steel holding carriage, raised and dropped in the same manner to produce the targeted velocity. A frozen, ice anvil (0.204 m diameter, 0.104 m thick) was used to reconstruct head-to-ice impacts (Figure 15c). Head-to-glass impacts were reconstructed using a piece of polycarbonate glass (0.012 m thick) measuring 1.83 m by 1.22 m (0.012 m thick) and secured by a wooden frame (Figure 15d).

Figure 15. *Head-to-boards, -ice, and -glass impact events using the monorail drop rig.*

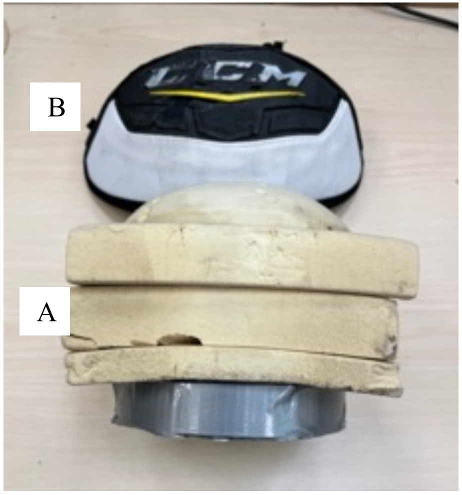
Note. Flat boards anvil (a), Angled (45°) boards anvil (b), Frozen ice anvil (c), Glass anvil (d).

3.6.2 Shoulder-to-Head Impact Events

The pneumatic linear impactor was used to simulate shoulder-to-head impact events (Figure 16) and was conducted in a similar manner to previous research by Rousseau (2014) and Rousseau and Hoshizaki (2015). The impacting end of the impacting arm was fitted with a medium compliance striker cap consisting of a 6.5 cm thick layer of vinyl nitrile (VN) 602 foam covered with a 0.025 m tall rounded VN cap and a CCM Ultra Tacks Pro shoulder pad (Figure 17).

Figure 16. *Shoulder-to-head impact events using the pneumatic linear impactor.*

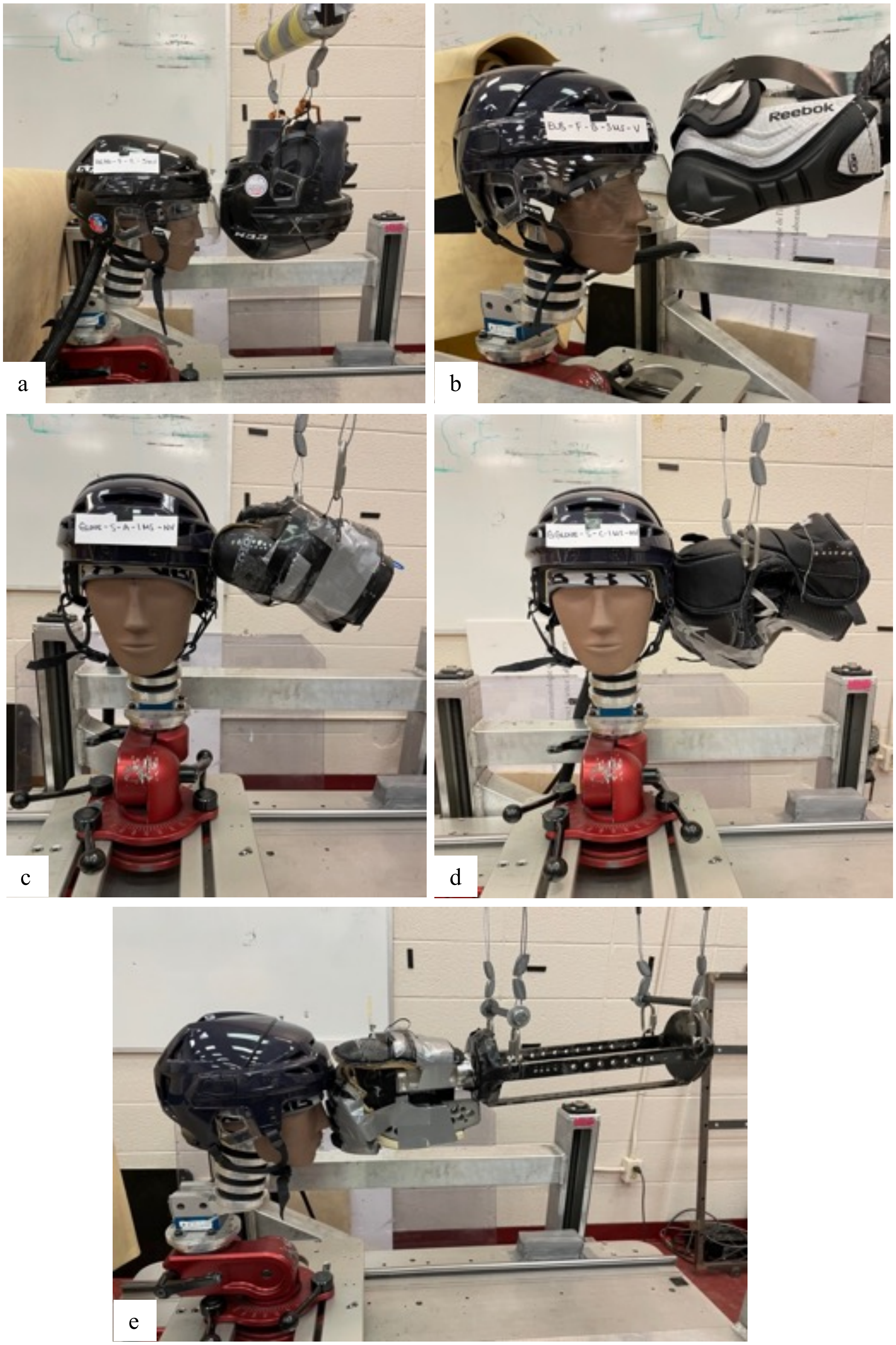
Figure 17. *Striker cap (*A*) and shoulder pad (*B*).*



3.6.3 Head-to-Head, Elbow-to-Head, Glove-to-Head, and Punch Impact Events

A pendulum impactor was used to simulate collision-type events (elbow-to-head, glove-to-head, head-to-head, punch) and was based on the methodology of previous research (Rousseau, 2014; Rousseau and Hoshizaki, 2015; Chen et al., 2020; Kendall, 2016; Post et al., 2020). Head-to-head impacts (Figure 18a) utilized a large NOCSAE head form (4.424 kg) (Figure 19) fitted with a CCM Vector 8 senior hockey helmet. Elbow-to-head impacts (Figure 18b) utilized an elbow striker anvil (6.2 kg), composed of an aluminum frame covered with a layer of ¼ inch VN 602 foam and an RBK11K elbow pad. For glove-to-head impact events, an ice hockey glove (skater; goalie) (Figure 20) was used with the added weight of 0.607 kg to the palm of each glove to simulate the average mass of the elite ice hockey players' hands from the 2003-04 and 2016-17 NHL ice hockey seasons (Clauser et al., 1969; Appendix C) (Figure 18c, 18d). Punch events utilized an impacting anvil (5.23 kg) composed of an aluminum frame covered with a layer of ¼ inch VN 602 foam and an adult ice hockey skater's glove (Figure 18e).

Figure 18. *Head-to-head, elbow-to-head, glove-to-head and punch impact events using the pendulum impactor.*



Note. Head-to-head impact events (a), elbow-to-head impact events (b), skater glove-to-head impact events (c), goalie glove-to-head impact events (d), punch impact events (e).

Figure 19. *NOCSAE head form, front (left) and front-diagonal (right)*.

Figure 20. *Skater (*A*) and goalie (*B*) gloves, with mass of hand (*C*).*

3.7 Finite Element Model

The University College Dublin Brain Trauma Model Version 2.0 (UCDBTM V2.0) was used to determine maximum principal strain (MPS) from the head impacts evaluated in the laboratory. The UCDBTM was originally developed by Horgan and Gilchrist (2003). It has since been altered to adopt new mechanical and sliding properties for tissues: introduction of a low coefficient of friction between the scalp and skull; mesh refinements throughout the model; incorporate accelerometer elements at the centre of gravity for a direct comparison between linear and rotational accelerations of the head; include more elements (approximately 185,000 elements); and, has components that compose the model that include the scalp, skull, pia, falx, tentorium, cerebrospinal fluid, grey and white matter, cerebellum, and brainstem (Table 7) (Trotta et al., 2020; Horgan & Gilchrist, 2003). The UCDBTM V2.0 was partially validated using adult post-mortem head subject research by Loyd et al. (2014) and Hardy et al. (2001; 2007). Brain strain values were calculated using the three-dimensional dynamic head response (acceleration-time) curves obtained from the laboratory head impact evaluations and applied to the centre of gravity of the FE model (Trotta et al., 2020). The simulations were conducted using ABAQUS explicit software (Dassault Systèmes, MA, USA).

Table 7. *Summary of the mechanical properties used in the UCDBTM V2.0; table obtained from Trotta et al., 2020.*

Region	Model	Density (kg/m^3)	Poisson's Ratio
Scalp	Hyperelastic (Ogden)	1133	~ 0.5
Cerebellum	Visco-hyperelastic	1060	~ 0.5
Grey matter	Visco-hyperelastic	1060	~ 0.5
Brainstem	Visco-hyperelastic	1060	~ 0.5
Cortical bone	Linear elastic	2000	0.22
Trabecular bone	Linear elastic	1300	0.24
Pia	Linear elastic	1130	0.45
CSF	Linear elastic	1000	~ 0.5
Facial bone	Linear elastic	2100	0.22
Ventricles	Visco-hyperelastic	1040	~ 0.5
White matter	Viscoelastic	1060	~ 0.5
Dura, falx and tentorium	Hyperelastic	1130	~ 0.5

3.8 Maximum Principal Strain Categories

Maximum principal strain (MPS) values calculated from the head impact evaluations in this study were calculated using a finite element model and classified into five levels of brain strain magnitudes in this study. These MPS levels were: *Very low* (0-7.9%); *Low* (8.0-16.9%); *Moderate* (17.0-25.9%); *High* (26-34.9%); and, *Very high* (35%+) (Table 8) (Post et al, 2020; Karton, Hoshizaki & Gilchrist, 2020). These levels were established to capture a spectrum of injury severity, based on event reconstructive research and anatomic tissue analysis associated with physiological brain tissue responses to axonal stretch and concussion outcomes. Within the very low levels of MPS, an influx of calcium ions has been shown to be induced at 5% MPS (Yuen et al., 2009). Encompassing the very low and low levels of MPS, 5-15% has been shown to cause function impairments in neuronal signal transmission (Margulies & Thibault, 1992; Bain & Meaney, 2000; Singh et al., 2006; Elkin & Morrison, 2007). Magnitudes of 19-30% MPS (moderate into high MPS levels) represent a 50% risk of sustaining a concussion measured in the white or grey matter of the cerebrum (Zhang et al., 2004; Bain & Meaney, 2000). Very high MPS levels designate head impacts that represent a 50% risk of loss of consciousness and persistent symptoms of concussion (Cournoyer, 2019; Post et al., 2015).

For frequency analyses, the MPS value calculated from each of the head impact evaluations was applied to every condition (impact event X location X elevation) within the same velocity category.

Table 8. *MPS levels.*

Very Low	**0-7.9%**
Low	**8.0-16.9%**
Moderate	**17.0-25.9%**
High	**26.0-34.9%**
Very High	**≥35.0%**

3.9 Statistical Analysis

3.9.1 Frequency

Statistical analyses were conducted using Jamovi 2.3.13, with α level set at $p < 0.05$ for significance. The frequency of confirmed head impacts were logged and categorized per game. Non-parametric Mann-Whitney U test was conducted to compare total frequency per game between the 2003-04 and 2016-17 season. Ten (10) Mann-Whitney U tests were conducted on the frequency of head impacts within each impact event type between the 2003-04 and 2016-17 seasons to determine statistical significance. To further identify if significant differences existed in frequency of punches (both within and outside regular game time), scrum events, and fighting events, four (4) Mann-Whitney U tests were completed.

3.9.2 Magnitude

The magnitudes of each condition were categorized into MPS levels for each season (2003-04 and 2016-17). Five Mann-Whitney U tests were used to compare frequency differences in each MPS level between the 2003-04 and 2016-17 seasons. To further identify if significant differences existed in frequency of MPS levels, analysis of each event type was completed using Mann-Whitney U tests (total of 26 tests; 4 head-to-ice, 4 head-to-boards, 5 head-to-glass, 2 head-to-head, 4 shoulder-to-head, 4 elbow-to-head, 1 glove-to-head, 2 punch).

CHAPTER 4: RESULTS

4.1 Video Analysis

There were 1187.37 and 1200 minutes of regular-season game play analyzed in the 2003-04 and 2016-17 seasons, respectively. The discrepancy can be explained in the 2003-04 season: Game 13 had 8 minutes, 8 seconds and Game 15 had 4 minutes, 30 seconds not captured on video. 142 logged head impacts were able to use Kinovea to calculate the inbound velocity. 117 logged head impacts had estimate inbound velocities.

The results of frequency used to inform head impact evaluations and MPS levels were presented by specific event type, location, elevation, and velocity. The complete research design of this thesis is outlined in the Appendix (Appendix D).

4.2 Frequency of Head Impacts

4.2.1 Total Frequency of Head Impacts

Total frequency of head impacts was completed for twenty 2003-04 and twenty 2016-17 regular-season games of men's professional ice hockey. The results of the Mann-Whitney U test indicated there was no significant difference of total head impact frequency per game between 2003-04 (M=6.2, SD=2.7) and 2016-17 (M=6.4, SD=2.3) U=193, p=0.848 (Table 9).

Table 9. *Total observed frequency of head impacts per game.*

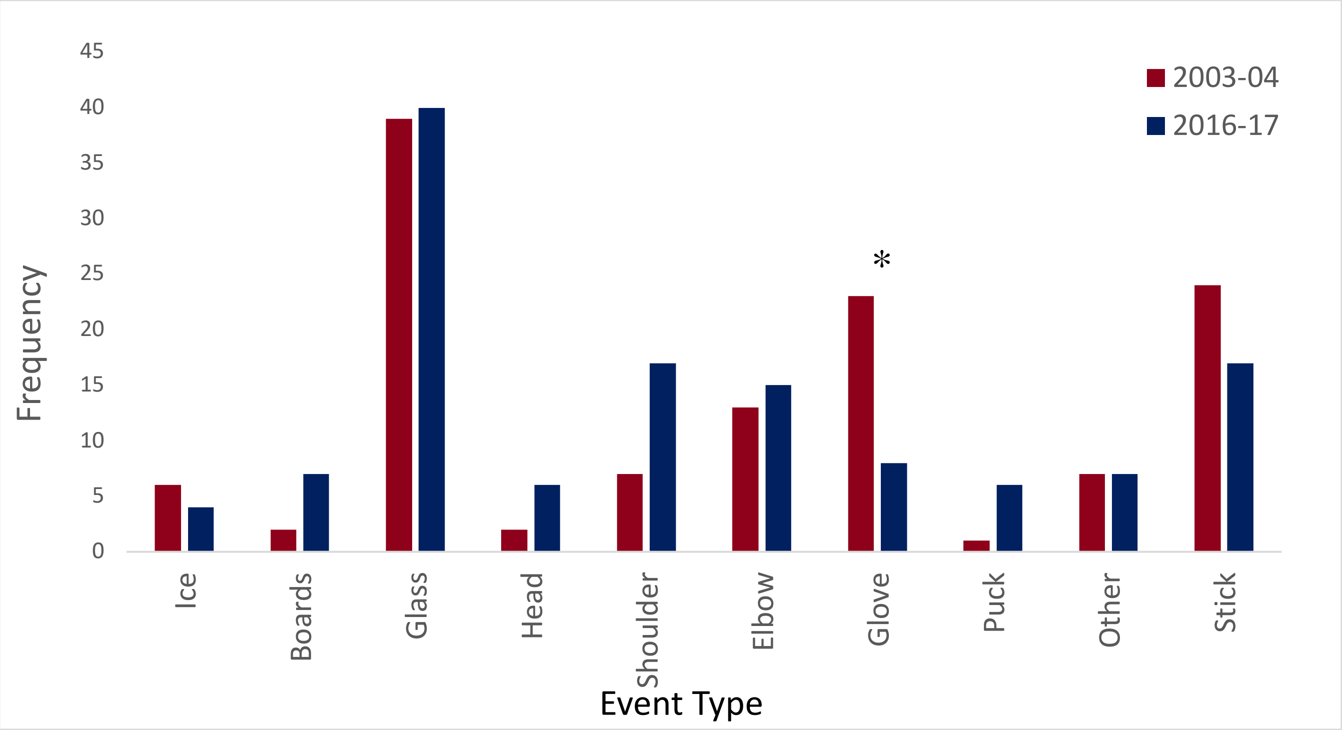
Game	2003-04	2016-17
1	10	6
2	13	4
3	5	8
4	8	5
5	6	9
6	3	8
7	7	5
8	4	7
9	2	6
10	8	7
11	8	9
12	6	5
13	9	8
14	4	3
15	5	5
16	6	3
17	7	4
18	6	8
19	5	12
20	2	
Total	**124**	**127**
Average	**6.2 (2.7)**	**6.4 (2.3)**

Note. See Appendix B, for breakdown of head impact frequency. Brackets indicate standard deviation.

4.2.2 Frequency of Head Impacts per Event Type

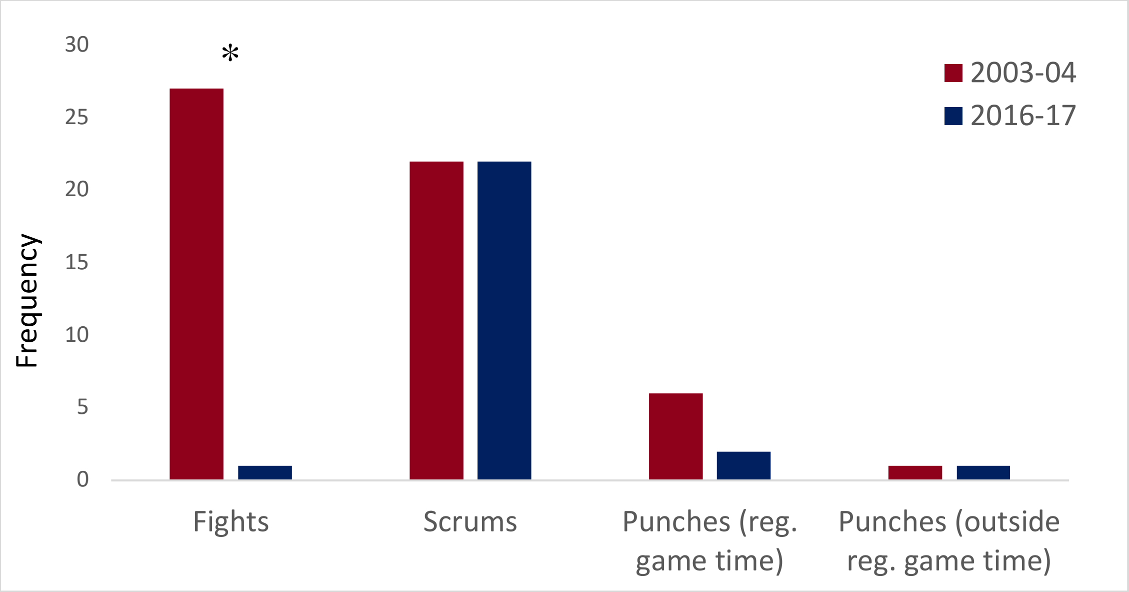
The frequency of head impact events was categorized into event types; head-to-ice, head-to-boards, head-to-glass, head-to-head, shoulder-to-head, elbow-to-head, glove-to-head, puck, stick, and other (Figure 21). The frequency was reported for fighting events: fights and scrums, and punches during and outside of regulation time (Figure 22) (described in Section 3.2.2).

Figure 21. *Observed frequency of head impact events in twenty games of 2003-04 and twenty games of 2016-17 North American men's professional ice hockey, by impact event type (excluding fighting events).*



Note. * indicates significance.

Figure 22. *Observed frequency of fighting events in twenty games of 2003-04 and twenty games of 2016-17 North American men's professional ice hockey, by event type.*



Note. * indicates significance.

Ten Mann-Whitney U tests were conducted comparing frequency of type of impact event between the seasons. The results indicated there were no significant differences of head impact frequency between the 2003-04 and 2016-17 seasons in the head-to-ice (U=188, p=0.668), head-to-boards (U=159, p=0.115), head-to-glass (U=194, p=0.879), head-to-head (U=180, p=0.310), shoulder-to-head (U=149, p=0.119), elbow-to-head (U=187, p=0.702), puck (U=160, p=0.081), stick (U=169, p=0.374), and other (U=194, p=0.842) event types. A significant difference of glove-to-head impact frequency was found between the 2003-04 and 2016-17 seasons (U=111, p=0.009).

Four Mann-Whitney U tests were conducted between the season and the type of impact event involving fighting events: fights, scrums, and punches. The results indicated there was significance difference in fight frequency between 2003-04 (M=1.4, SD=1.6) and 2016-17 (M=0.2, SD=0.2) U=86, p<0.001. There was no significant difference indicated by the results for scrum frequency between 2003-04 (M=1.1, SD=1.1) and 2016-17 (M=0.8, SD=1.1) U=183, p=0.626. The results for punch frequencies inside and outside regulation time, indicated no significant differences between 2003-04 and 2016-17 in either event (*Punches inside reg. time*: M=0.8, SD=0.3, U=188, p=0.588; *Punches outside reg. time*: M=0.3, SD=0.1, U=200, p=1.000).

4.3 Head Impact Evaluations

A total 117 head impacts were reconstructed for this thesis; 6 head-to-ice events, 8 head-to-boards events, 23 head-to-glass events, 7 head-to-head events, 19 shoulder-to-head events, 24 elbow-to-head events, 22 glove-to-head events, and 8 punch events. Of the 117 reconstructed head impacts, 21 impact conditions did not trigger the head form accelerometers set below 2 g. These conditions consisted of 1 elbow-to-head event, 19 glove-to-head events, and 1 punch event. As a result, MPS magnitude was not able to be calculated for these events. However, it could be reasonably inferred that these 21 head impacts would result in MPS magnitudes <8.0%, given the MPS response elicited from similar impact reconstructions (Appendix E). Therefore, these 21 head impacts were assigned to the '*very low*' MPS level for the frequency analyses as further described in Section 4.4 and 4.5. The dynamic response and UCDBTM V2.0 outputs for the reconstructed events are shown in Table 10.

Table 10. *Averages of the dynamic response and UCDBTM V2.0 outputs for all reconstructed events.*

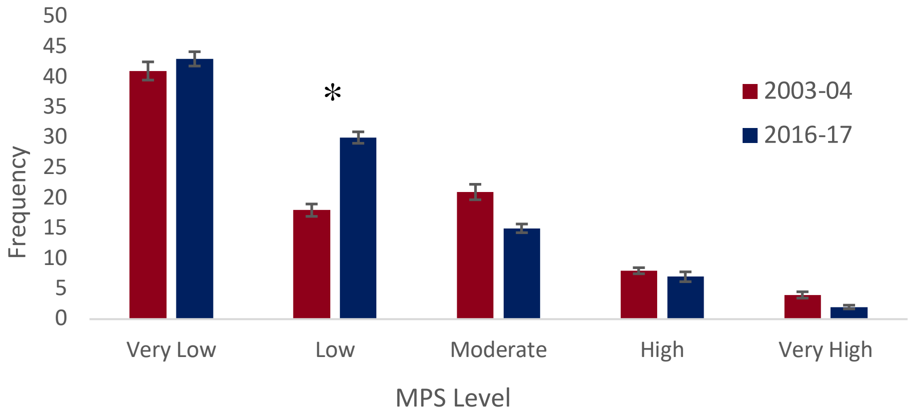
		Peak resultant acceleration			
Event	Season	Linear (g)	Rotational (rad/s^2)	Rotational velocity (rad/s)	MPS
Glass	2003-04	28.67 (18.16)	2081.44 (1413.42)	13.56 (7.48)	0.179 (0.099)
	2016-17	15.33 (8.27)	1119.16 (731.36)	10.75 (5.51)	0.110 (0.050)
Boards	2003-04	17.17 (2.75)	1129.52 (226.88)	10.47 (1.79)	0.091 (0.013)
	2016-17	40.99 (37.57)	2028.32 (1505.84)	11.56 (5.36)	0.215 (0.165)
Ice	2003-04	63.11 (16.13)	4464.81 (902.72)	24.47 (1.34)	0.361 (0.058)
	2016-17	45.23 (26.32)	3050.33 (1734.86)	17.69 (7.70)	0.277 (0.126)
Head	2003-04	4.07 (0.45)	395.88 (60.11)	8.05 (3.63)	0.033 (0.003)
	2016-17	18.03 (20.84)	1337.91 (1479.25)	10.96 (7.45)	0.112 (0.121)
Shoulder	2003-04	13.82 (7.77)	926.41 (454.75)	13.96 (6.87)	0.138 (0.079)
	2016-17	13.09 (5.88)	900.62 (406.15)	14.85 (6.50)	0.143 (0.068)
Elbow	2003-04	14.10 (11.55)	1081.22 (887.43)	11.23 (6.13)	0.121 (0.094)
	2016-17	13.23 (9.56)	1169.62 (849.14)	13.56 (6.78)	0.120 (0.076)
Glove	2003-04	3.10 (0.55)	380.10 (38.63)	6.32 (0.63)	0.038 (0.002)
	2016-17	3.20 (0.10)	325.30 (17.58)	4.50 (0.92)	0.040 (N/A)
Punch	2003-04	10.63 (5.83)	680.79 (357.76)	10.62 (4.40)	0.094 (0.053)
	2016-17	3.07 (0.92)	237.55 (70.21)	6.13 (1.78)	0.035 (0.011)

Note. Brackets indicate standard deviation.

4.4 Frequency of Magnitude of Head Impacts

Frequency of MPS values of head impact evaluations were binned into five MPS levels. Five Mann-Whitney U tests were conducted to compare frequency of head impact magnitude between 2003-04 and 2016-17 in each MPS level. It was determined there were no significant differences of frequency in the very low (U=186, p=0.698), moderate (U=183, p=0.634), high (U=168, p=0.287), and very high (U=189, p=0.621) MPS levels. The statistical results showed 2016-17 had significantly higher frequency in the low category, U=130, p=0.050 (Figure 23).

Figure 23. *Comparison of MPS level distribution of head impact frequency.*



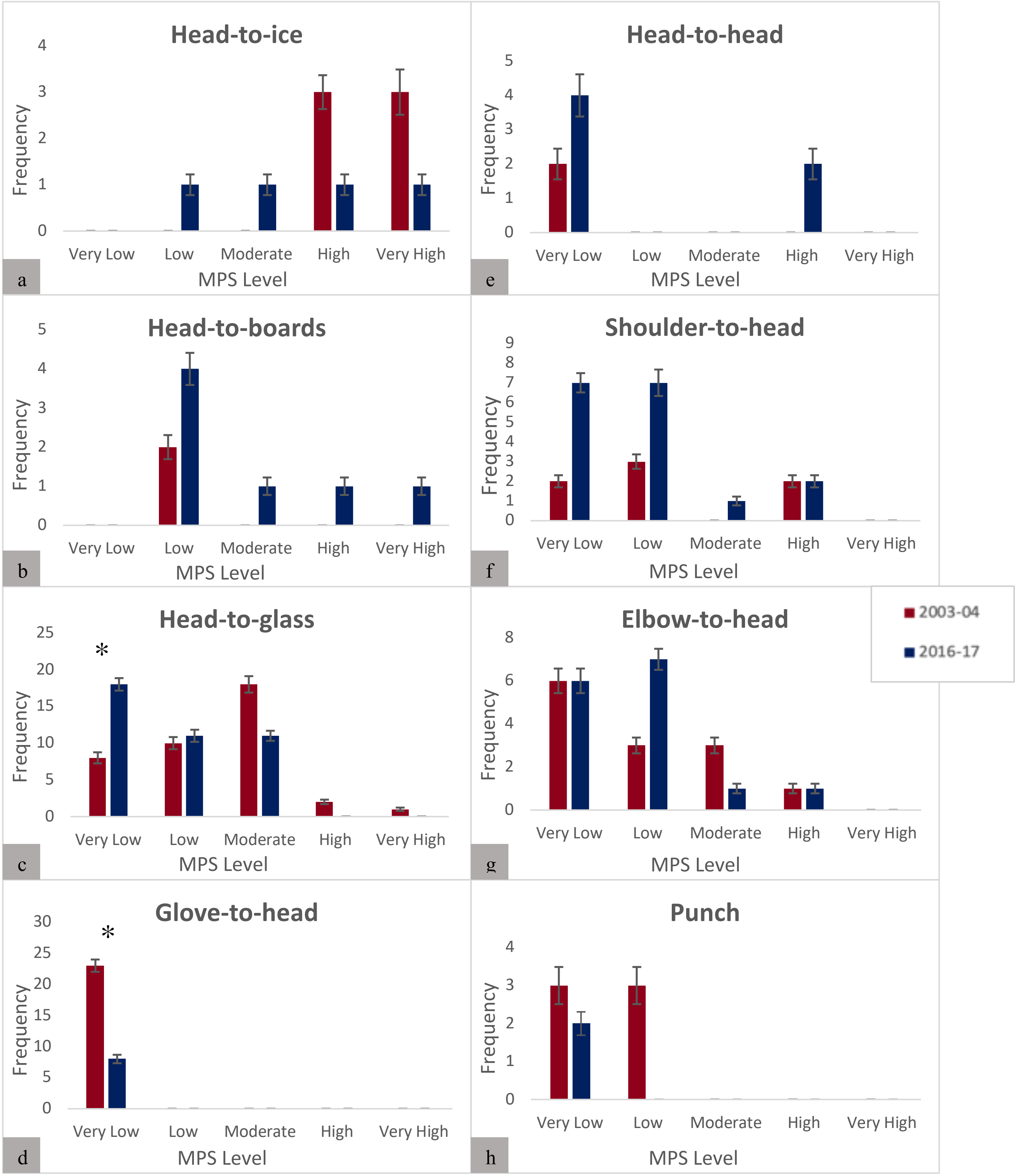
Note. * indicates significance.

4.5 Frequency-Magnitude of Event Types

Frequency of MPS values were designated a level of MPS based on head impact event type. Five Mann-Whitney U tests were conducted for each event type to examine differences in frequency of head impact magnitude between 2003-04 and 2016-17 in each MPS level.

Head-to-ice events contained no observed head impact frequency within the very low MPS level, and no significant differences were found in the low (U=190, p=0.342), moderate (U=190, p=0.342), high (U=180, p=0.310) or very high (U=190, p=0.554) MPS levels (Figure 24a). Head-to-boards events contained no observed head impact frequency within the very low MPS level, and no significant differences were found in the low (U=180, p=0.394), moderate (U=190, p=0.342), high (U=190, p=0.342) or very high (U=190, p=0.342) MPS levels (Figure 24b). Head-to-glass events were found to have significant difference in the very low MPS level for frequency of head impacts (U=131, p=0.040), with higher frequency documented in the 2016-17 season. No other differences were observed in other MPS levels for head-to-glass events (*low*: U=195, p=0.886; *moderate*: U=172, p=0.414; *high*: U=180, p=0.162; *very high*: U=190, p=0.342) (Figure 24c). Head-to-head events contained no observed head impact frequency within the low, moderate and very high MPS levels, and no significant differences were found in the very low (U=190, p=0.573) or high (U=190, p=0.342) MPS levels (Figure 24e). Shoulder-to-head impacts contained no observed head impact frequency within the very high MPS level, and no significant differences were found in the very low (U=150, p=0.064), low (U=177, p=0.382), moderate (U=190, p=0.342) or high (U=200, p=1.000) MPS levels (Figure 24f). Elbow-to-head events contained no observed head impact frequency within the very high MPS level, and no significant differences were found in the very low (U=200, p=1.000), low (U=160, p=0.154), moderate (U=180, p=0.310) or high (U=200, p=1.000) MPS levels (Figure 24g). Glove-to-head events contained no observed head impact frequency within the low, moderate, high and very high MPS levels. Glove-to-head events within the very low MPS level had a significantly higher frequency of head impacts in the 2003-04 season (U=111, p=0.009) (Figure 24d). Punch events contained no observed head impact frequency within the moderate, high and very high MPS levels, and no significant differences were found in the very low (U=199, p=0.979) or low (U=180, p=0.163) MPS levels (Figure 24h).

Figure 24. *Comparison of MPS level distribution of overall head impact frequency per event type.*



Note. * indicates significance.

CHAPTER 5: DISCUSSION

This study compared head impact frequency and frequency of brain strain magnitudes between the 2003-04 and 2016-17 seasons of professional North American ice hockey games. More specifically, this study compared total frequency of head impacts, frequency of head impacts of various event types, and frequency of MPS levels between 2003-04 and 2016-17. The purpose of this research was to evaluate whether the numerous rule changes that have occurred over the past two decades have had an effect on head impact frequency and brain strain magnitude when comparing these two seasons of ice hockey. These comparisons can provide valuable information into the potential brain trauma profile for current professional ice hockey players, in addition to the effect of rule changes made to the game over the last two decades, which has implications for brain trauma exposure and short- and long-term brain health outcomes.

5.1 Frequency of Head Impacts

Overall frequency of head impacts between twenty 2003-04 and twenty 2016-17 regular season ice hockey games were not statistically significant. Frequency of head impacts are important in brain trauma analysis as research has reported association between frequency of impacts and changes in brain structure, metabolic characteristics, and indication of injury through blood and CSF biomarkers and imaging changes in white matter following a season of ice hockey play without diagnosed or reported injuries (Bazarian et al., 2012; Breedlove et al., 2012; Bahrami et al., 2016; Slobounov et al., 2017; Kuzminski et al., 2018; Neselius et al., 2012; Shahim et al., 2017; Sollmann et al., 2018; McAllister & McCrea, 2017; Koerte et al., 2012). The findings of this thesis are consistent with prior reports by Donaldson and colleagues (2013) and McKay and colleagues (2013). These results demonstrate today's players experience similar frequencies of brain trauma from head impacts in ice hockey when compared to players in 2003-04 and may be at the same level of risk for neurological degenerative diseases (McKee et al., 2010). Donaldson and colleagues (2013) reported no significant decrease in the frequency of concussions or suspected concussions in the NHL in the three seasons before, during and after the illegal head contact rule (Rule 48) had been implemented in 2010. This thesis found no significant differences in head impacts in the moderate or more severe MPS levels.

Glove-to-head impacts were the third most frequent event type in the 2003-04 season, and the fifth most frequent in the 2016-17 season, with a significant decrease (Figure 21). Glove-to-head impacts are high compliance events that involved low inbound velocities and below. With these lower velocities combined with the high compliance of the glove(s), the MPS values that this study documented were all contained with the very low MPS category as the energy that moved through the brain was very low inflicting very low amount of trauma (Figure 24; Appendix E). The lower frequency of glove-to-head events may have been a result of the changes in the rules over the last two decades that directly involve the glove to the head and penalize players for this type of contact. Specifically, the rule implemented in the 2014-15 season that penalizes players who grab an opponent's face mask (visor or cage) may have contributed to the decrease in glove-to-head observed frequency (National Hockey League Official Rules 2014-15, 2014).

Head impacts involving the glass have remained the most frequent event type in both the 2003-04 and 2016-17 seasons with 39 and 40 observed head-to-glass impacts, respectively. Head-to-glass events are of a low compliance. This event had logged velocities within the very low, low, and medium velocity bins. As demonstrated in previous research, as compliance is lowered, duration is lower and MPS increases. The MPS values this study resulted in for glass events were in all five MPS categories. Due to the hard impacting surface, the energy that moves through the brain is higher. The wide range of MPS that this study demonstrated could be explained by the three different inbound velocities in addition to the location and elevation of each specific impact condition, as location and elevation has been shown to influence the brain strain magnitude. Over the twenty games of each season analyzed in this thesis, it was observed players experienced this specific event type 39 times (SD=1.39) in 2003-04 and 40 (SD=1.26) in 2016-17. These results demonstrate a large portion of the total head impacts is occurring along the perimeter of the ice rink and is consistent with previous research. Aguiar and colleagues (2020) reported 30% of the 449 total head impacts were head-to-glass impacts with glass impacts being the most frequency event type. Hutchison and colleagues (2013) reported 53% of head contact events occurred along the perimeter of the ice rink during the 2006 to 2010 NHL seasons. Rules implemented over the past two decades may have contributed to the increased head impacts involving and around the perimeter of the ice rink found in this thesis.

Fighting events were also investigated in this thesis. Fighting events were broken down into three categories (fights, scrums, punches) to better classify the frequency and magnitude of punches and are defined in Section 3.2.2. The frequency of fights was found to have been significantly decreased from 2003-04 to 2016-17. Within the twenty 2016-17 regular season games analyzed in this thesis, there was one fight observed during regular game time. Fighting has been reported to be decreasing in the NHL (Plassche et al., 2022). The decrease in fighting frequency in regular season games could be attributed to the number of rules implemented in the last two decades to deter players from fighting (Marek, 2015; National Hockey League Official Rules 2014-15, 2014; “Historical Rule Changes”, n.d.). However, fight frequency may be influenced by overtime and/or playoff season games, where more aggressive plays occur

(McKay et al., 2013). Fighting has been associated with the reduction of brain volume and greater cognitive impairments (Banks et al., 2014; Bernick et al., 2015). As of 2019, there have been twelve reported cases of chronic traumatic encephalopathy (CTE), or brain degeneration, in retired, deceased NHL players, with the latest professional athlete retiring from the sport in 2014 (Westhead, 2019). This study can suggest that the decrease in fighting during regular game time can be stated to have made the game safer in terms of long-term brain health as players are sustaining a lower exposure to head impacts from fights.

5.2 Frequency-Magnitude of Head Impacts

Present day ice hockey players sustained similar impact magnitudes as those in 2003-04. The highest frequency of head impact magnitudes occurred in the very low MPS level within both seasons of ice hockey, which may not have resulted in acute physical signs or symptoms of brain trauma, but still may contribute to long-term effects with increased exposure (Hoshizaki et al., 2013; Yuen et al., 2009) (Figure 23). Statistical significance was found within the low MPS level, with the 2016-17 regular season showing a significantly higher frequency of magnitude when compared to the 2003-04 regular season (Figure 23). This finding may be due to the professional athletes' increasing their skills and performance at checking and using their bodies instead of their gloves. Rule changes have opened up the game on the ice, allowing for more movement. More movement on the ice means more opportunities for collisions and brain trauma. These collisions were shown in this study as head-to-glass, head-to-boards, shoulder-to-head and elbow-to-head events. Player's heads are experiencing more head impacts with low compliant surfaces (boards and glass) as well as with more compliant surfaces (shoulder and elbow) that allow for more force to transfer to the head and through the brain from higher than previously experienced inbound velocities. The more frequent head impacts in conjunction with higher inbound velocities attributes to the higher frequency of lower MPS values seen in this study (Figure 23; Appendix E). These results demonstrate that players are experiencing an increase in repetitive low-magnitude brain strains which have been linked with long-term negative health outcomes.

To further analyze if there were significant differences in frequency of MPS levels, impact event types were analyzed. Statistical analysis revealed significance within two event types: head-to-glass and glove-to-head. In the 2016-17 regular season, there was a significant increase in head-to-glass event frequency and a significant decrease in glove-to-head event frequency when compared to the 2003-04 regular season.

Head-to-glass impact events in the very low MPS level increased significantly in the 2016-17 ice hockey season by 2.25 times. The total number of head-to-glass impacts did not change from the 2003-04 season to the 2016-17 season (2003-04 was observed to have 39 head-to-glass impacts and 40 impacts in 2016-17), the shift that the 2016-17 season had to include a higher frequency of very low MPS level could depict that players are impacting the glass, either accidently or intentionally from an opponent, with a lower force than previously observed. The results reveal a trend that in 2016 there were observed to be more very low and low levels of MPS in comparison to in 2003 containing more moderate levels of MPS. High and very high MPS levels from head-to-glass impacts were documented in 2003 only. The rule changes may have allowed for less force from bodychecking into the glass where the energy transferred from the impactor's body to the impacted player's brain was lower, which was seen as the lower magnitude levels; however, the frequency of these lower-magnitude strains increased. This increase in repetitive low-magnitude brain strain has the ability to cause cumulative brain trauma, implicating brain health negatively, in both short- and long-term outcomes.

Glove-to-head impacts involving the goalie's catcher glove was only observed in the 2003-04 season. While the goalie catcher glove had a higher mass (0.911 kg) compared to the skater glove (0.352 kg), glove-to-head impacts demonstrated magnitude strains in the very low MPS level only, within both seasons, with the 2016-17 season demonstrating a decrease in frequency-magnitude of MPS. This decrease could be contributed to rules that have directly addressed fighting and face contact, where players may be using their hands less as points of contact with opponent's head and using their bodies more. This may also be demonstrated by the increase in frequency of head-to-glass events observed in this thesis' results from the 2016-17 season.

CHAPTER 6: CONCLUSION

The purpose of this study was to compare head impact frequency and frequency of brain strain magnitude sustained by players before and after a series of rule changes were implemented in professional ice hockey. This was completed by comparing total frequency of head impacts, frequency of head impacts per event type, and frequency of magnitude levels of head impacts. The results revealed no differences for total frequency of head impacts between 2003-04 and 2016-17 regular season games. Glove-to-head impact frequency was found to have significantly decreased from 2003-04 to 2016-17. Head-to-glass events remained as the event type with the highest frequency in both seasons. No other differences were found for frequency of head impacts per event type. Fighting events were analyzed and 2016-17 was found to have a significantly lower number of fights compared to 2003-04. For frequency-magnitudes, the results revealed 2016-17 had a significantly higher frequency in the low MPS level. When event type frequency-magnitudes were examined, the results revealed a significant increase in head-to-glass events and a significant decrease in glove-to-head events in 2016-17 from 2003-04.

This study found present day players sustain similar impact magnitudes as players in 2003-04, with the exception of low MPS level head impacts occurring at a higher frequency in the 2016-17 season. Repetitive low-magnitude strains result may result in long-term brain health implications. Given the popularity of ice hockey nationally, internationally, and globally, sport organizations should investigate further rule changes on head impacts in the game of ice hockey, specifically decreasing the number of head-to-glass events. Future studies could investigate whether rule changes have an effect on pre- and post-season game play when compared to in-season games. Head impacts sustained during overtime should also be investigated to determine if players are at a higher risk of brain trauma compared to regulation time. Rules have been implemented and changed over the last few decades that change how the game of ice hockey is played and how athletes are exposed to brain trauma. This study provides useful information for understanding of the professional ice hockey environment for protective equipment manufacturers as well as other stakeholders in the sport.

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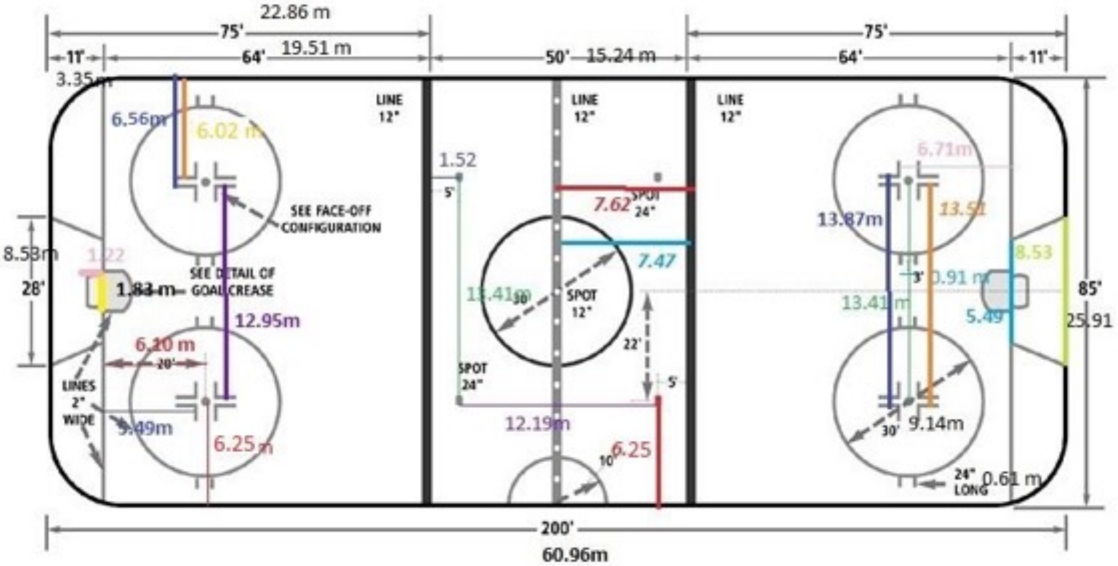
APPENDICES

Appendix A

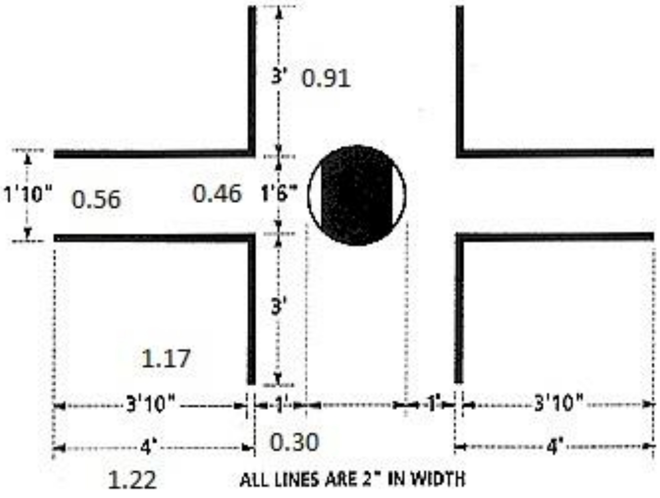
Figure 25. *Rink dimensions and ice surface measurements for an NHL-sized ice hockey rink.*



Boards height = 1.07
Glass height= 2.44
Glass width = 1.52

Goal posts heigt= 1.23
Width= 1.83

Figure 26. *Face-off circle measurements for an NHL-sized ice hockey rink.*



Appendix B

Table 11. *Logged confirmed head impacts from video analysis during the 2003-04 season of professional ice hockey.*

Game No.	Event Type	Location of Impact	Velocity Bin	Placement	Board Anvil
GAME 1	glove to head	side	very low	above	
GAME 1	head to glass	Rear Boss	Low	above	
GAME 1	head to glass	side	Very Low	above	
GAME 1	glove to head	Rear Boss	Very Low	below	
GAME 1	head to glass	Rear	Low	center	
GAME 1	head to ice	Rear	Low	center	
GAME 1	Other	Side	Very Low	center	
GAME 1	head to ice	Rear	Low	center	
GAME 1	glove to head	Rear Boss	Low	below	
GAME 1	stick	Front	/	center	
GAME 1	punch	Front boss	Low	center	
GAME 1	punch	Front	Very low	below	
GAME 1	punch	rear	low	below	
GAME 2	glove to head	Side	Very Low	center	
GAME 2	head to boards	Front Boss	Very Low	above	angled
GAME 2	head to glass	Rear	low	above	flat
GAME 2	head to glass	Front Boss	Very Low	center	
GAME 2	glove to head	Rear	Very Low	above	
GAME 2	head to shoulder	Side	Very Low	center	
GAME 2	head to elbow	Front	Very Low	below	
GAME 2	glove to head	Crown	Very Low	/	
GAME 2	head to elbow	Side	Low	above	
GAME 2	stick	Front	/	below	
GAME 2	stick	Front boss	/	above	
GAME 2	stick	Side	/	above	
GAME 2	stick	Front boss	/	above	
GAME 2	punch	Rear boss	Very low	below	
GAME 2	punch	rear	Very low	below	
GAME 3	head to elbow	Front	Very Low	above	
GAME 3	other	Front	Very Low	above	
GAME 3	head to elbow	Front	Very Low	below	
GAME 3	stick	Front boss	/	center	
GAME 3	stick	front	/	below	
GAME 4	head to elbow	Rear Boss	very low	above	

GAME 4	head to glass	Side	Low	center
GAME 4	head to glass	Rear	Very Low	above
GAME 4	glove to head	Front Boss	Low	center
GAME 4	head to glass	Rear Boss	Med	center
GAME 4	head to glass	Side	Low	center
GAME 4	stick	Side	/	below
GAME 4	stick	Side	/	above
GAME 5	head to glass	Side	Very Low	above
GAME 5	head to glass	Front Boss	Low	above
GAME 5	head to glass	Rear Boss	Very Low	center
GAME 5	head to glass	Side	Med	above
GAME 5	stick	Front	/	center
GAME 5	stick	Front	/	above
GAME 6	head to glass	Front Boss	low	above
GAME 6	head to ice	Side	Low	above
GAME 6	stick	Front	/	above
GAME 7	glove to head	Side	Very Low	below
GAME 7	head to glass	Side	Very Low	above
GAME 7	head to elbow	Side	low	center
GAME 7	head to glass	Rear	Very Low	above
GAME 7	glove to head	Front Boss	Very Low	center
GAME 7	head to ice	Front Boss	Low	center
GAME 7	head to glass	Side	Very Low	above
GAME 8	head to glass	Side	Low	center
GAME 8	glove to head	Crown	Very Low	/
GAME 8	head to elbow	rear	Very Low	above
GAME 8	stick	Front	/	above
GAME 9	head to glass	Side	Very Low	above
GAME 9	stick	Front	/	above
GAME 10	glove to head	front	Very Low	center
GAME 10	head to elbow	Side	Very Low	below
GAME 10	head to shoulder	Front	Low	below
GAME 10	head to ice	Rear	Low	center
GAME 10	glove to head	Front Boss	Very Low	center
GAME 10	stick	Front boss	/	below
GAME 10	stick	Front boss	/	above
GAME 10	stick	Front	/	center
GAME 11	other	Side	Med	below
GAME 11	head to glass	Rear	Low	center
GAME 11	head to shoulder	Side	Low	center

GAME 11	glove to head	Rear Boss	Very Low	above	
GAME 11	glove to head	Rear	Very Low	center	
GAME 11	head to glass	Front Boss	Very Low	above	
GAME 11	stick	Front boss	/	center	
GAME 11	stick	Front	/	below	
GAME 12	glove to head	Side	Very Low	center	
GAME 12	head to glass	Front Boss	Med	center	
GAME 12	other	Front Boss	Very Low	center	
GAME 12	head to head	Side	Very Low	above	
GAME 12	head to head	Front Boss	Very Low	above	
GAME 12	stick	Rear boss	/	center	
GAME 13	head to glass	Side	Low	above	
GAME 13	other	side	Med	above	
GAME 13	head to shoulder	Side	Med	center	
GAME 13	head to glass	Front Boss	Low	center	
GAME 13	head to glass	Rear	Low	center	
GAME 13	head to elbow	Front	Low	below	
GAME 13	head to elbow	Front Boss	Low	center	
GAME 13	head to glass	Rear	Low	center	
GAME 13	glove to head	Side	Very Low	above	
GAME 14	glove to head	Front	low	below	
GAME 14	glove to head	Front Boss	Very Low	below	
GAME 14	stick	Front boss	/	below	
GAME 14	stick	Front	/	below	
GAME 15	head to elbow	Side	Med	center	
GAME 15	head to glass	Side	Low	above	
GAME 15	glove to head	Front	low	below	
GAME 15	head to glass	Side	Low	above	
GAME 15	glove to head	Side	Very Low	center	
GAME 16	head to boards	Crown	Very Low	/	flat
GAME 16	head to shoulder	Front	low	center	
GAME 16	head to shoulder	Front	very low	center	
GAME 16	head to glass	Rear Boss	Very Low	above	
GAME 16	glove to head	Front Boss	Very Low	below	
GAME 16	stick	Front boss	/	above	
GAME 17	other	Rear	Very Low	center	
GAME 17	head to glass	Front Boss	Low	above	
GAME 17	head to elbow	Front Boss	Low	center	
GAME 17	head to glass	Rear Boss	Low	center	
GAME 17	head to shoulder	Side	Med	center	
GAME 17	head to glass	Front Boss	Very Low	center	

GAME 17	head to glass	Side	Very Low	center	
GAME 17	punch	rear	low	center	
GAME 18	head to glass	front boss	Low	above	
GAME 18	head to glass	Side	Low	center	
GAME 18	other	Front	Low	center	
GAME 18	head to ice	Side	Low	center	
GAME 18	head to glass	Side	Low	center	
GAME 18	stick	Front	/	below	
GAME 19	puck	Front Boss	Very High	below	
GAME 19	head to glass	Rear Boss	Low	above	
GAME 19	glove to head	Front Boss	Very Low	center	
GAME 19	head to glass	Side	Low	above	
GAME 19	head to elbow	Side	Low	below	
GAME 20	head to glass	Front Boss	Low	above	
GAME 20	glove to head	Side	Very Low	above	

Table 12. *Logged confirmed head impacts from video analysis during the 2016-17 season of professional ice hockey.*

Game No.	Event Type	Location of Impact	Velocity Bin	Placement	Board Anvil
GAME 1	head to glass	Side	low	above	
GAME 1	head to elbow	Rear Boss	low	above	
GAME 1	puck	Front	Very High	above	
GAME 1	head to boards	Rear Boss	Very Low	above	angled
GAME 1	puck	Side	Very High	above	
GAME 1	head to glass	Rear Boss	Low	center	
GAME 1	punch	Side	Very low	center	
GAME 2	other	Side	Very Low	center	
GAME 2	head to glass	Rear Boss	Low	center	
GAME 2	head to glass	rear boss	Very Low	above	
GAME 2	stick	Front	/	center	
GAME 3	head to shoulder	Side	Very Low	center	
GAME 3	head to glass	Side	Very Low	above	
GAME 3	head to glass	Side	Low	above	
GAME 3	head to ice	Front Boss	Low	center	
GAME 3	head to glass	Front Boss	Very Low	above	
GAME 3	other	Side	High	center	
GAME 3	puck	Side	Very High	center	
GAME 3	head to shoulder	Rear Boss	Low	above	

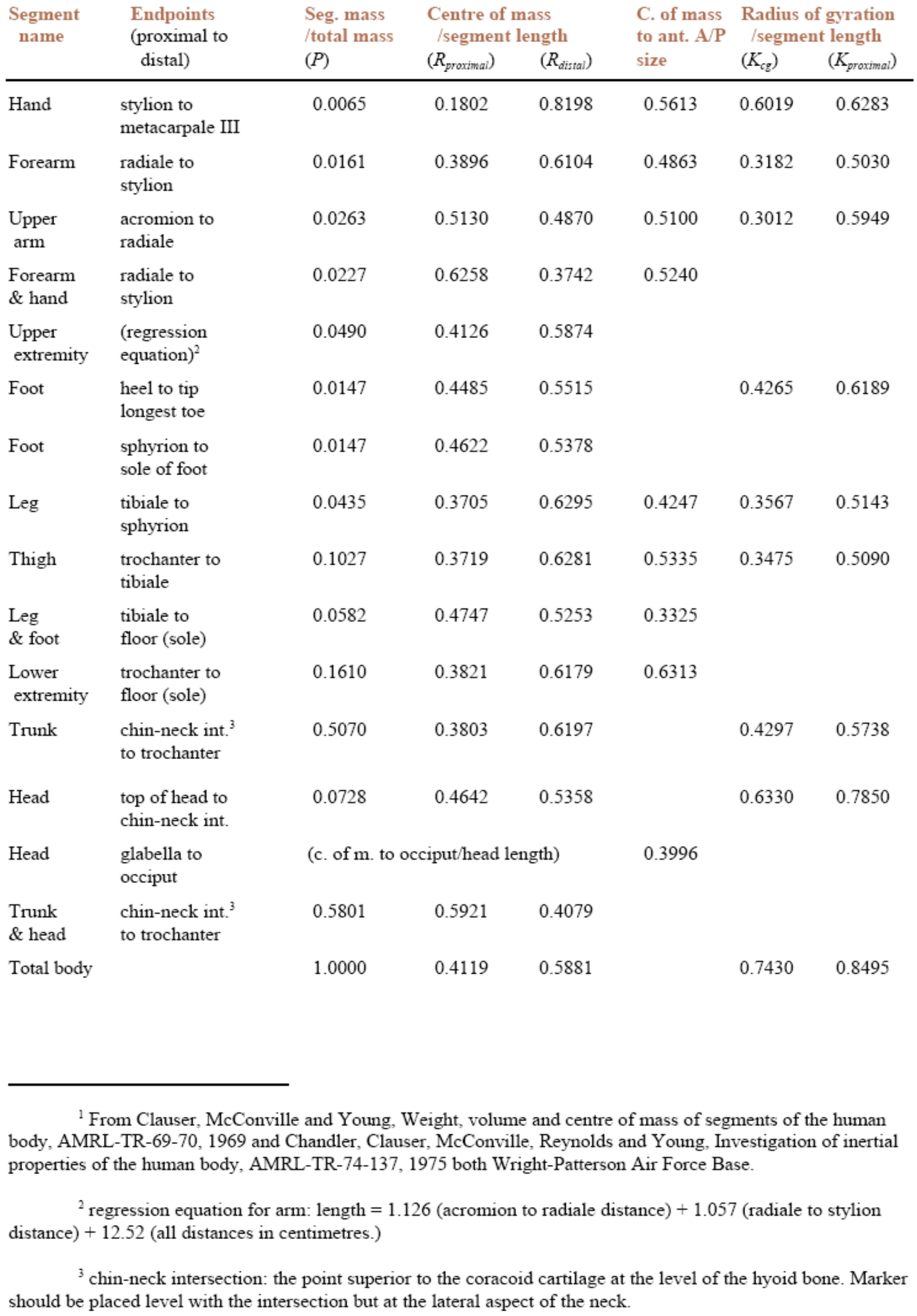
GAME 4	head to glass	Side	low	above	
GAME 4	head to elbow	Front	Low	below	
GAME 4	head to glass	Side	Very Low	above	
GAME 4	head to glass	Front	Very Low	center	
GAME 4	stick	Front boss	/	center	
GAME 5	head to elbow	Side	low	below	
GAME 5	head to shoulder	Front	low	below	
GAME 5	head to shoulder	Side	low	above	
GAME 5	head to glass	Front Boss	Very Low	center	
GAME 5	head to head	Side	Very Low	center	
GAME 5	head to head	Side	Very Low	above	
GAME 5	head to shoulder	Side	Low	below	
GAME 5	stick	Front boss	/	center	
GAME 5	stick	Rear	/	above	
GAME 6	head to shoulder	Front	low	center	
GAME 6	head to glass	Rear	very low	above	
GAME 6	head to elbow	Front Boss	Low	below	
GAME 6	head to glass	Front Boss	Very Low	center	
GAME 6	head to shoulder	Front	low	center	
GAME 6	head to shoulder	Crown	Very Low	/	
GAME 6	head to elbow	Side	Very low	center	
GAME 6	stick	Front	/	below	
GAME 7	head to head	Front Boss	Very Low	above	
GAME 7	head to head	Rear Boss	Very Low	center	
GAME 7	other	Crown	Very Low	/	
GAME 7	glove to head	Front Boss	Very Low	center	
GAME 7	head to shoulder	Front Boss	Low	above	
GAME 8	head to shoulder	Front Boss	Med	below	
GAME 8	head to glass	Rear	Very Low	center	
GAME 8	head to boards	Side	Very Low	above	flat
GAME 8	head to elbow	Side	low	center	
GAME 8	head to elbow	Side	Very Low	center	
GAME 8	other	Rear	Low	above	
GAME 8	stick	Front	/	below	
GAME 9	glove to head	Side	Very Low	center	
GAME 9	head to glass	Rear Boss	Low	center	
GAME 9	head to glass	Rear Boss	Low	center	
GAME 9	head to glass	Side	Very Low	center	
GAME 9	head to glass	Side	Very Low	center	
GAME 9	stick	Front boss	/	below	
GAME 10	head to shoulder	Side	Low	center	

GAME 10	head to shoulder	Rear Boss	Very Low	center	
GAME 10	head to glass	Side	Very Low	above	
GAME 10	other	Rear Boss	very low	center	
GAME 10	head to boards	Rear Boss	Very Low	above	angled
GAME 10	head to ice	Rear	Low	center	
GAME 10	stick	Front boss	/	below	
GAME 11	puck	Rear Boss	Very high	below	
GAME 11	other	Rear Boss	Low	center	
GAME 11	head to elbow	Front Boss	Very Low	below	
GAME 11	head to ice	Side	Very Low	above	
GAME 11	head to boards	Side	Low	above	flat
GAME 11	other	Side	Low	center	
GAME 11	head to glass	Rear Boss	Very Low	center	
GAME 11	head to glass	Side	Very Low	center	
GAME 11	head to elbow	Crown	Very Low		
GAME 12	head to glass	Front Boss	very low	center	
GAME 12	head to glass	Rear Boss	Very Low	above	angled
GAME 12	head to glass	Side	Very Low	center	
GAME 12	head to shoulder	Front Boss	Very Low	center	
GAME 12	stick	Side	/	below	
GAME 13	head to shoulder	Front Boss	Med	center	
GAME 13	head to glass	Front Boss	Very Low	above	
GAME 13	head to glass	Rear Boss	Very Low	center	
GAME 13	head to glass	Front Boss	Very Low	above	
GAME 13	head to elbow	Rear Boss	Very Low	below	
GAME 13	head to glass	Rear Boss	Very Low	center	
GAME 13	head to elbow	Side	Med	center	
GAME 13	stick	Front boss	/	below	
GAME 14	head to elbow	Front	Low	center	
GAME 14	head to glass	Side	Low	above	
GAME 14	head to glass	Side	Very Low	above	
GAME 15	glove to head	Front	Very Low	below	
GAME 15	glove to head	Side	Very Low	below	
GAME 15	head to boards	Front Boss	Very Low	center	flat
GAME 15	stick	Front	/	center	
GAME 15	stick	Front boss	/	above	
GAME 16	glove to head	Front Boss	Very Low	below	
GAME 16	glove to head	Front	Very Low	center	
GAME 16	head to glass	Front Boss	Very Low	center	
GAME 17	head to elbow	Front	Low	below	
GAME 17	puck	Side	Very High	above	

GAME 17	head to glass	Front Boss	Very Low	center	
GAME 17	stick	Front boss	/	center	
GAME 18	glove to head	Side	Low	above	
GAME 18	head to glass	Rear Boss	Low	above	
GAME 18	head to glass	Side	Very Low	above	
GAME 18	head to elbow	Front Boss	Very Low	above	
GAME 18	head to glass	Front Boss	Very Low	above	
GAME 18	head to glass	Rear	Very Low	center	
GAME 18	stick	Front boss	/	center	
GAME 18	stick	Front boss	/	below	
GAME 19	head to ice	Front	Very Low	above	
GAME 19	head to head	front	Med	center	
GAME 19	head to head	Side	Med	center	
GAME 19	head to shoulder	Side	Med	centre	
GAME 19	head to shoulder	Side	Low	above	
GAME 19	puck	Front Boss	Very High	center	
GAME 19	head to boards	Rear	Low	center	flat
GAME 19	head to boards	Side	Very Low	center	angled
GAME 19	head to elbow	Front Boss	Low	above	
GAME 19	head to glass	Rear Boss	Low	center	
GAME 19	stick	Front boss	/	below	
GAME 19	stick	Front boss	/	below	
GAME 19	punch	Front	Very low	center	
GAME 20	head to shoulder	Front Boss	Very Low	center	
GAME 20	glove to head	Rear Boss	Low	below	
GAME 20	head to glass	Rear	Very Low	center	
GAME 20	head to glass	Front Boss	Low	center	
GAME 20	head to glass	Rear Boss	Very Low	center	

Appendix C

Table 13. *Clauser's table of body segment parameters for 2-D studies; table obtained from Clauser et al., 1969.*



Segment name	**Endpoints** (proximal to distal)	**Seg. mass /total mass** (*P*)	**Centre of mass /segment length** ($R_{proximal}$)	(R_{distal})	**C. of mass to ant. A/P size**	**Radius of gyration /segment length** (K_{cg})	($K_{proximal}$)
Hand	stylion to metacarpale III	0.0065	0.1802	0.8198	0.5613	0.6019	0.6283
Forearm	radiale to stylion	0.0161	0.3896	0.6104	0.4863	0.3182	0.5030
Upper arm	acromion to radiale	0.0263	0.5130	0.4870	0.5100	0.3012	0.5949
Forearm & hand	radiale to stylion	0.0227	0.6258	0.3742	0.5240		
Upper extremity	(regression equation)[2]	0.0490	0.4126	0.5874			
Foot	heel to tip longest toe	0.0147	0.4485	0.5515		0.4265	0.6189
Foot	sphyrion to sole of foot	0.0147	0.4622	0.5378			
Leg	tibiale to sphyrion	0.0435	0.3705	0.6295	0.4247	0.3567	0.5143
Thigh	trochanter to tibiale	0.1027	0.3719	0.6281	0.5335	0.3475	0.5090
Leg & foot	tibiale to floor (sole)	0.0582	0.4747	0.5253	0.3325		
Lower extremity	trochanter to floor (sole)	0.1610	0.3821	0.6179	0.6313		
Trunk	chin-neck int.[3] to trochanter	0.5070	0.3803	0.6197		0.4297	0.5738
Head	top of head to chin-neck int.	0.0728	0.4642	0.5358		0.6330	0.7850
Head	glabella to occiput	(c. of m. to occiput/head length)			0.3996		
Trunk & head	chin-neck int.[3] to trochanter	0.5801	0.5921	0.4079			
Total body		1.0000	0.4119	0.5881		0.7430	0.8495

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[1] From Clauser, McConville and Young, Weight, volume and centre of mass of segments of the human body, AMRL-TR-69-70, 1969 and Chandler, Clauser, McConville, Reynolds and Young, Investigation of inertial properties of the human body, AMRL-TR-74-137, 1975 both Wright-Patterson Air Force Base.

[2] regression equation for arm: length = 1.126 (acromion to radiale distance) + 1.057 (radiale to stylion distance) + 12.52 (all distances in centimetres.)

[3] chin-neck intersection: the point superior to the coracoid cartilage at the level of the hyoid bone. Marker should be placed level with the intersection but at the lateral aspect of the neck.

Appendix D

Table 14. *Impact characteristics (obtained from video analysis) used for head impact evaluations for the 2003-04 season of professional ice hockey.*

Event Type	***Velocity Bin***	***Impact Location***	***Impact Elevation***	***Boards Anvil***	***Code***
Head-to-ice	3 m/s	Front Boss	Centre		ICE-FB-C-3MS
		Side	Above		ICE-S-A-3MS
		Side	Centre		ICE-S-C-3MS
		Rear	Centre		ICE-R-C-3MS
Head-to-boards	1 m/s	Front Boss	Above	Angled	BANG-FBPA-A-1MS
		Crown	/	Flat	BFLAT-CR-1MS
Head-to-glass	1 m/s	Front Boss	Above		GLASS-FBPA-A-1MS-NV
		Front Boss	Centre		GLASS-FB-C-1MS-NV
		Side	Above		GLASS-S-A-1MS
		Side	Centre		GLASS-S-C-1MS
		Rear Boss	Centre		GLASS-RB-C-1MS
		Rear	Above		GLASS-R-A-1MS
	3 m/s	Front Boss	Above		GLASS-FBPA-A-3MS-NV
		Front Boss	Centre		GLASS-FB-C-3MS-NV
		Side	Above		GLASS-S-A-3MS
		Side	Centre		GLASS-S-C-3MS
		Rear Boss	Above		GLASS-RBNA-A-3MS
		Rear Boss	Centre		GLASS-RB-C-3MS
		Rear	Above		GLASS-R-A-3MS
		Rear	Centre		GLASS-R-C-3MS
	5 m/s	Front Boss	Centre		GLASS-FB-C-5MS-NV
		Side	Above		GLASS-S-A-5MS
		Rear Boss	Centre		GLASS-RB-C-5MS
Head-to-head	1 m/s	Front Boss	Above		HEAD-FBPA-A-1MS-NV
		Side	Above		HEAD-S-A-1MS
Shoulder-to-head	1 m/s	Front	Centre		SHO-F-C-1MS-NV
		Side	Centre		SHO-S-C-1MS-NV
	3 m/s	Front	Centre		SHO-F-C-3MS-NV
		Front	Below		SHO-F-B-3MS-NV
		Side	Centre		SHO-S-C-3MS-NV
	5 m/s	Side	Centre		SHO-S-C-5MS-NV
Elbow-to-head	1 m/s	Front	Above		ELB-F-A-1MS-NV
		Front	Below		ELB-F-B-1MS-NV
		Side	Below		ELB-S-A-1MS-NV
		Rear Boss	Above		ELB-RBNA-A-1MS
		Rear	Above		ELB-R-A-1MS
	3 m/s	Front	Below		ELB-F-B-3MS-NV
		Front Boss	Centre		ELB-FB-C-3MS-NV
		Side	Above		ELB-S-A-3MS-NV

		Side	Centre		ELB-S-C-3MS-NV
		Side	Below		ELB-S-B-3MS-NV
	5 m/s	Side	Centre		ELB-S-C-5MS-NV
Glove-to-head (skater glove)	1 m/s	Front	Centre		GLOVE-F-C-1MS-NV
		Front Boss	Centre		GLOVE-FB-C-1MS-NV
		Front Boss	Below		GLOVE-FBPA-B-1MS-NV
		Side	Above		GLOVE-S-A-1MS-NV
		Side	Centre		GLOVE-S-C-1MS-NV
		Side	Below		GLOVE-S-B-1MS-NV
		Rear Boss	Below		GLOVE-RBNA-B-1MS
		Rear	Above		GLOVE-R-A-1MS
		Crown	/		GLOVE-CR-1MS
	3 m/s	Front	Below		GLOVE-F-B-3MS-NV
		Front Boss	Centre		GLOVE-FB-C-3MS-NV
		Rear Boss	Below		GLOVE-RBNA-B-3MS
Glove-to-head (goalie glove)	1 m/s	Side	Centre		GGLOVE-S-C-1MS-NV
		Rear Boss	Above		GGLOVE-RBNA-A-1MS
		Rear	Centre		GGLOVE-R-C-1MS
Punch	1 m/s	Front	Below		PUNCH-F-B-1MS-NV
		Rear Boss	Below		PUNCH-RBNA-B-1MS
		Rear	Below		PUNCH-R-B-1MS
	3 m/s	Front	Below		PUNCH-F-B-3MS-NV
		Rear	Centre		PUNCH-R-C-3MS
		Rear	Below		PUNCH-R-B-3MS

Table 15. *Impact characteristics (obtained from video analysis) used for head impact evaluations for the 2016-17 season of professional ice hockey.*

Event Type	***Velocity Bin***	***Impact Location***	***Impact Elevation***	***Boards Anvil***	***Code***
Head-to-ice	1 m/s	Front	Above		ICE-F-A-1MS-V
		Side	Above		ICE-S-A-1MS
	3 m/s	Front Boss	Centre		ICE-FB-C-3MS-V
		Rear	Centre		ICE-R-C-3MS
Head-to-boards	1 m/s	Front Boss	Centre	Flat	BFLAT-FB-C-1MS-V
		Side	Above	Flat	BFLAT-S-A-1MS
		Side	Centre	Angled	BANG-S-C-1MS
		Rear Boss	Above	Angled	BANG-RBNA-A-1MS
	3 m/s	Side	Above	Flat	BFLAT-S-A-3MS
		Rear	Centre	Flat	BFLAT-R-C-3MS
Head-to-glass	1 m/s	Front	Centre		GLASS-F-C-1MS-V
		Front Boss	Above		GLASS-FBPA-A-1MS-V
		Front Boss	Centre		GLASS-FB-C-1MS-V
		Side	Above		GLASS-S-A-1MS
		Side	Centre		GLASS-S-C-1MS

		Rear Boss	Above		GLASS-RBNA-A-1MS
		Rear Boss	Centre		GLASS-RB-C-1MS
		Rear	Above		GLASS-R-A-1MS
		Rear	Centre		GLASS-R-C-1MS
		Crown	/		GLASS-CR-1MS
	3 m/s	Front Boss	Centre		GLASS-FB-C-3MS-V
		Side	Above		GLASS-S-A-3MS
		Rear Boss	Above		GLASS-RB-A-3MS
		Rear Boss	Centre		GLASS-RB-C-3MS
Head-to-head	1 m/s	Front Boss	Above		HEAD-FBPA-A-1MS-V
		Side	Above		HEAD-S-A-1MS
		Side	Centre		HEAD-S-C-1MS
		Rear Boss	Centre		HEAD-RB-C-1MS
	5 m/s	Front	Centre		HEAD-F-C-5MS-V
		Side	Centre		HEAD-S-C-5MS
Shoulder-to-head	1 m/s	Front Boss	Centre		SHO-FB-C-1MS-V
		Side	Centre		SHO-S-C-1MS-V
		Rear Boss	Centre		SHO-RB-C-1MS
		Crown	/		SHO-CR-1MS
	3 m/s	Front	Centre		SHO-F-C-3MS-V
		Front	Below		SHO-F-B-3MS-V
		Front Boss	Above		SHO-FBPA-A-3MS-V
		Side	Above		SHO-S-A-3MS-V
		Side	Centre		SHO-S-C-3MS-V
		Side	Below		SHO-S-B-3MS-V
		Rear Boss	Above		SHO-RBNA-A-3MS
	5 m/s	Front Boss	Centre		SHO-FB-C-5MS-V
		Front Boss	Below		SHO-FBPA-B-5MS-V
Elbow-to-head	1 m/s	Front Boss	Above		ELB-FBPA-A-1MS-V
		Front Boss	Below		ELB-FBPA-B-1MS-V
		Side	Centre		ELB-S-C-1MS-V
		Rear Boss	Below		ELB-RBNA-B-1MS
		Crown	/		ELB-CR-1MS
	3 m/s	Front	Centre		ELB-F-C-3MS-V
		Front	Below		ELB-F-B-3MS-V
		Front Boss	Above		ELB-FBPA-A-3MS-V
		Front Boss	Below		ELB-FBPA-B-3MS-V
		Side	Centre		ELB-S-C-3MS-V
		Side	Below		ELB-S-B-3MS-V
		Rear Boss	Above		ELB-RBNA-A-3MS
	5 m/s	Side	Centre		ELB-S-C-5MS-V
Glove-to-head (skater glove)	1 m/s	Front	Centre		GLOVE-F-C-1MS-V
		Front	Below		GLOVE-F-B-1MS-V
		Front Boss	Centre		GLOVE-FB-C-1MS-V
		Front Boss	Below		GLOVE-FBPA-B-1MS-V

		Side	Centre		GLOVE-S-C-1MS-V
		Side	Below		GLOVE-S-B-1MS-V
	3 m/s	Side	Above		GLOVE-S-A-3MS-V
		Rear Boss	Below		GLOVE-RBNA-B-3MS-V
Punch	1 m/s	Front	Centre		PUNCH-F-C-1MS-V
		Side	Centre		PUNCH-S-C-1MS-V

Appendix E

Table 16. *Dynamic head response and MPS values for each head impact evaluation.*

GLASS

	Lin Accel (a)	Rot Accel (α)	Rot Vel (ω)	MPS
GLASS-FBPA-A-1MS-V-1	8.6	543.9	5.5	7.8%
GLASS-FBPA-A-1MS-V-2	9.3	502.2	6.8	
GLASS-FBPA-A-1MS-V-3	9.4	537.7	5.2	
Mean	9.1	527.9	5.8	
SD	0.4	22.5	0.9	

	Lin Accel (a)	Rot Accel (α)	Rot Vel (ω)	MPS
GLASS-FBPA-A-1MS-NV-1	9.5	541.6	4.7	8.4%
GLASS-FBPA-A-1MS-NV-2	9.3	512.4	7.3	
GLASS-FBPA-A-1MS-NV-3	10.1	581.3	5.1	
Mean	9.6	545.1	5.7	
SD	0.4	34.6	1.4	

	Lin Accel (a)	Rot Accel (α)	Rot Vel (ω)	MPS
GLASS-FBPA-A-3MS-NV-1	26.5	1354.3	10.2	13.3%
GLASS-FBPA-A-3MS-NV-2	25.8	1416.0	10.1	
GLASS-FBPA-A-3MS-NV-3	25.5	1587.6	10.7	
Mean	25.9	1452.6	10.3	
SD	0.5	120.9	0.3	

	Lin Accel (a)	Rot Accel (α)	Rot Vel (ω)	MPS
GLASS-S-A-1MS-1	9.6	480.2	4.0	7.4%
GLASS-S-A-1MS-2	9.1	651.1	5.0	
GLASS-S-A-1MS-3	9.8	793.9	6.5	
Mean	9.5	641.7	5.2	
SD	0.4	157.1	1.3	

	Lin Accel (a)	Rot Accel (α)	Rot Vel (ω)	MPS
GLASS-S-A-3MS-1	24.1	1300.00	9.1	17.1%
GLASS-S-A-3MS-2	25.3	1263.5	8.6	
GLASS-S-A-3MS-3	25.0	1261.7	8.6	
Mean	24.8	1275.1	8.8	
SD	0.6	21.6	0.3	

	Lin Accel (a)	Rot Accel (α)	Rot Vel (ω)	MPS

GLASS-S-A-5MS-1	47.2	2729.9	15.5	26.9%
GLASS-S-A-5MS-2	48.9	2886.4	16.1	
GLASS-S-A-5MS-3	50.7	3063.0	16.7	
Mean	48.9	2893.1	16.1	
SD	1.8	166.7	0.6	

	Lin Accel (a)	Rot Accel (α)	Rot Vel (ω)	MPS
GLASS-RBNA-A-1MS-2	8.2	743.0	6.7	7.9%
GLASS-RBNA-A-1MS-3	8.0	725.1	7.2	
Mean	8.1	734.1	7.0	
SD	0.1	12.7	0.4	

	Lin Accel (a)	Rot Accel (α)	Rot Vel (ω)	MPS
GLASS-RBNA-A-3MS-1	24.8	2513.0	16.6	18.6%
GLASS-RBNA-A-3MS-2	25.6	2617.6	16.0	
GLASS-RBNA-A-3MS-3	27.7	2214.6	14.5	
Mean	26.0	2448.4	15.7	
SD	1.5	209.1	1.1	

	Lin Accel (a)	Rot Accel (α)	Rot Vel (ω)	MPS
GLASS-R-A-1MS-1	8.3	293.9	3.6	5.7%
GLASS-R-A-1MS-2	9.8	473.2	5.3	
GLASS-R-A-1MS-3	9.3	373.9	2.1	
Mean	9.1	380.3	3.7	
SD	0.8	89.8	1.6	

	Lin Accel (a)	Rot Accel (α)	Rot Vel (ω)	MPS
GLASS-R-A-3MS-1	28.0	1138.3	3.3	17.4%
GLASS-R-A-3MS-2	28.8	877.2	2.4	
GLASS-R-A-3MS-3	27.1	531.8	1.8	
Mean	28.0	849.1	2.5	
SD	0.9	304.2	0.8	

	Lin Accel (a)	Rot Accel (α)	Rot Vel (ω)	MPS
GLASS-R-C-1MS-1	11.8	828.2	6.8	9.0%
GLASS-R-C-1MS-2	11.6	912.6	9.5	
GLASS-R-C-1MS-3	12.6	949.1	8.9	
Mean	12.0	896.6	8.4	
SD	0.5	62.0	1.4	

	Lin Accel (a)	Rot Accel (α)	Rot Vel (ω)	MPS
GLASS-R-C-3MS-1	30.6	2282.5	14.8	21.6%
GLASS-R-C-3MS-2	33.4	2440.0	14.8	
GLASS-R-C-3MS-3	33.2	2523.9	15.6	

Mean	32.4	2415.5	15.1
SD	1.6	122.6	0.5

	Lin Accel (a)	Rot Accel (α)	Rot Vel (ω)	MPS
GLASS-FB-C-1MS-NV-1	12.7	1421.5	11.1	11.7%
GLASS-FB-C-1MS-NV-2	13.2	1464.3	10.8	
GLASS-FB-C-1MS-NV-3	13.6	1515.4	10.8	
Mean	13.2	1467.1	10.9	
SD	0.5	47.0	0.2	

	Lin Accel (a)	Rot Accel (α)	Rot Vel (ω)	MPS
GLASS-FB-C-3MS-NV-1	36.9	3039.9	13.6	
GLASS-FB-C-3MS-NV-2	39.9	3034.5	12.2	23.0%
GLASS-FB-C-3MS-NV-3	27.4	3261.6	16.6	
Mean	34.7	3112.0	14.1	
SD	6.5	129.6	2.2	

	Lin Accel (a)	Rot Accel (α)	Rot Vel (ω)	MPS
GLASS-FB-C-5MS-NV-1	78.1	4884.1	19.3	45.5%
GLASS-FB-C-5MS-NV-2	70.4	5408.4	20.8	
GLASS-FB-C-5MS-NV-3	70.2	5533.5	20.5	
Mean	72.9	5275.3	20.2	
SD	4.5	344.5	0.8	

	Lin Accel (a)	Rot Accel (α)	Rot Vel (ω)	MPS
GLASS-FB-C-1MS-V-1	7.0	476.6	8.5	6.3%
GLASS-FB-C-1MS-V-2	10.1	626.0	11.7	
GLASS-FB-C-1MS-V-3	8.7	568.5	9.7	
Mean	8.6	557.0	10.0	
SD	1.6	75.4	1.6	

	Lin Accel (a)	Rot Accel (α)	Rot Vel (ω)	MPS
GLASS-FB-C-3MS-V-1	23.2	1429.5	17.5	17.2%
GLASS-FB-C-3MS-V-2	23.1	1253.8	16.5	
GLASS-FB-C-3MS-V-3	26.1	1460.2	15.9	
Mean	24.1	1381.2	16.6	
SD	1.7	111.4	0.8	

	Lin Accel (a)	Rot Accel (α)	Rot Vel (ω)	MPS
GLASS-F-C-1MS-V-1	7.7	418.5	8.1	6.7%
GLASS-F-C-1MS-V-2	8.9	508.4	7.1	

GLASS-F-C-1MS-V-3	8.8	479.9	4.9	
Mean	8.5	468.9	6.7	
SD	0.7	45.9	1.6	

	Lin Accel (a)	Rot Accel (α)	Rot Vel (ω)	MPS
GLASS-RB-C-1MS-1	10.8	1232.0	14.9	10.8%
GLASS-RB-C-1MS-2	9.2	1519.1	17.0	
GLASS-RB-C-1MS-3	12.5	1459	13.9	
Mean	10.8	1403.4	15.3	
SD	1.7	151.4	1.6	

	Lin Accel (a)	Rot Accel (α)	Rot Vel (ω)	MPS
GLASS-RB-C-3MS-1	32.6	2889.1	22.5	18.6%
GLASS-RB-C-3MS-2	32.7	2770.0	23.0	
GLASS-RB-C-3MS-3	31.1	2452.7	21.9	
Mean	32.1	2703.9	22.5	
SD	0.9	225.6	0.6	

	Lin Accel (a)	Rot Accel (α)	Rot Vel (ω)	MPS
GLASS-RB-C-5MS-1	58.9	4724.6	32.7	30.9%
GLASS-RB-C-5MS-2	62.6	5128.7	32.3	
GLASS-RB-C-5MS-3	62.8	5027.9	32.0	
Mean	61.4	4960.4	32.3	
SD	2.2	210.3	0.4	

	Lin Accel (a)	Rot Accel (α)	Rot Vel (ω)	MPS
GLASS-S-C-1MS-1	14.5	1076.2	13.3	9.7%
GLASS-S-C-1MS-2	13.7	1004.2	13.0	
GLASS-S-C-1MS-3	14.0	925.8	12.5	
Mean	14.1	1002.1	12.9	
SD	0.4	75.2	0.4	

	Lin Accel (a)	Rot Accel (α)	Rot Vel (ω)	MPS
GLASS-S-C-3MS-1	33.0	2566.2	19.4	17.5%
GLASS-S-C-3MS-2	34.9	2629.9	20.0	
GLASS-S-C-3MS-3	33.7	2481.9	18.7	
Mean	33.9	2559.3	19.4	
SD	1.0	74.2	0.7	

BOARDS

	Lin Accel (a)	Rot Accel (α)	Rot Vel (ω)	MPS
BFLAT-CR-1MS-1	21.0	1333.7	11.5	
BFLAT-CR-1MS-2	17.3	1173.2	10.3	8.2%
BFLAT-CR-1MS-3	19.7	1292.2	10.5	
Mean	19.3	1266.4	10.8	
SD	1.9	83.3	0.6	

	Lin Accel (a)	Rot Accel (α)	Rot Vel (ω)	MPS
BFLAT-FB-C-1MS-1	25.4	829.0	4.6	19.3%
BFLAT-FB-C-1MS-3	23.9	622.6	5.3	
Mean	24.7	725.8	5.0	
SD	1.1	145.9	0.5	

	Lin Accel (a)	Rot Accel (α)	Rot Vel (ω)	MPS
BFLAT-S-A-1MS-1	16.0	1399.5	11.7	10.1%
BFLAT-S-A-1MS-2	15.2	1399.8	14.9	
BFLAT-S-A-1MS-3	21.6	1217.7	10.8	
Mean	17.6	1339.0	12.5	
SD	3.5	105.0	2.2	

	Lin Accel (a)	Rot Accel (α)	Rot Vel (ω)	MPS
BFLAT-S-A-3MS-1	53.7	3560.9	21.1	27.4%
BFLAT-S-A-3MS-2	59.6	4606.4	24.4	
BFLAT-S-A-3MS-3	74.8	4033.3	16.8	
Mean	62.7	4066.9	20.8	
SD	10.9	523.6	3.8	

	Lin Accel (a)	Rot Accel (α)	Rot Vel (ω)	MPS
BFLAT-R-C-3MS-1	105.9	3893.6	10.8	52.1%
BFLAT-R-C-3MS-2	110.6	3669.5	10.4	
BFLAT-R-C-3MS-3	111.6	3979.5	10.8	
Mean	109.4	3847.5	10.7	
SD	3.0	160.1	0.2	

	Lin Accel (a)	Rot Accel (α)	Rot Vel (ω)	MPS
BANG-S-C-1MS-1	14.5	768.5	8.0	11.8%
BANG-S-C-1MS-2	11.6	773.8	5.1	
BANG-S-C-1MS-3	17.1	1303.8	10.0	
Mean	14.4	948.7	7.7	
SD	2.8	307.5	2.5	

	Lin Accel (a)	Rot Accel (α)	Rot Vel (ω)	MPS
BANG-RBNA-A-1MS-1	11.3	1230.9	12.9	8.5%
BANG-RBNA-A-1MS-2	12.7	575.5	7.7	
BANG-RBNA-A-1MS-3	11.4	617.1	11.3	
Mean	11.8	807.8	10.6	
SD	0.8	367.0	2.7	

	Lin Accel (a)	Rot Accel (α)	Rot Vel (ω)	MPS
BANG-FBPA-A-1MS-1	13.7	730.9	13.3	10.0%
BANG-FBPA-A-1MS-2	15.6	1004.5	8.6	
BANG-FBPA-A-1MS-3	15.7	1242.6	8.6	
Mean	15.0	992.7	10.2	
SD	1.1	256.1	2.7	

ICE

	Lin Accel (a)	Rot Accel (α)	Rot Vel (ω)	MPS
ICE-F-A-1MS-1	22.9	1219.4	10.0	16.7%
ICE-F-A-1MS-2	24.4	1293.1	9.7	
ICE-F-A-1MS-3	22.3	1296.7	9.0	
Mean	23.2	1269.7	9.6	
SD	1.1	43.6	0.5	

	Lin Accel (a)	Rot Accel (α)	Rot Vel (ω)	MPS
ICE-S-A-1MS-1	25.1	1610.0	11.0	19.2%
ICE-S-A-1MS-2	27.5	1800.3	11.4	
ICE-S-A-1MS-3	28.0	1832.7	11.1	
Mean	26.9	1747.7	11.2	
SD	1.6	120.3	0.2	

	Lin Accel (a)	Rot Accel (α)	Rot Vel (ω)	MPS
ICE-S-A-3MS-1	61.4	3291.5	22.2	34.5%
ICE-S-A-3MS-2	61.0	3403.4	22.0	
ICE-S-A-3MS-3	65.5	3808.8	23.3	
Mean	62.6	3501.2	22.5	
SD	2.5	272.2	0.7	

	Lin Accel (a)	Rot Accel (α)	Rot Vel (ω)	MPS
ICE-FB-C-3MS-1	41.9	3659.2	25.0	30.5%
ICE-FB-C-3MS-2	45.5	3880.9	24.4	
ICE-FB-C-3MS-3	47.2	3864.2	23.9	
Mean	44.9	3801.4	24.4	
SD	2.7	123.5	0.6	

	Lin Accel (a)	Rot Accel (α)	Rot Vel (ω)	MPS
ICE-S-C-3MS-1	52.2	4966.5	25.4	34.9%
ICE-S-C-3MS-2	63.4	5549.4	25.4	

ICE-S-C-3MS-3	61.2	5006.3	25.2
Mean	58.9	5174.1	25.3
SD	5.9	325.7	0.1

	Lin Accel (a)	Rot Accel (α)	Rot Vel (ω)	MPS
ICE-R-C-3MS-1	78.3	4966.1	26.0	
ICE-R-C-3MS-2	84.7	5297.5	25.8	44.3%
ICE-R-C-3MS-3	95.0	5883.9	25.0	
Mean	86.0	5382.5	25.6	
SD	8.4	464.8	0.5	

HEAD

	Lin Accel (a)	Rot Accel (α)	Rot Vel (ω)	MPS
HEAD-S-A-1MS-1	4.5	355.4	7.0	3.5%
HEAD-S-A-1MS-2	4.6	514.2	15.4	
HEAD-S-A-1MS-3	4.3	368.3	6.7	
Mean	4.5	412.6	9.7	
SD	0.2	88.2	4.9	

	Lin Accel (a)	Rot Accel (α)	Rot Vel (ω)	MPS
HEAD-FBPA-A-1MS-NV-1	3.7	385.8	7.0	3.1%
HEAD-FBPA-A-1MS-NV-2	3.6	356.3	5.8	
HEAD-FBPA-A-1MS-NV-3	3.7	395.3	6.4	
Mean	3.7	379.1	6.4	
SD	0.1	20.3	0.6	

	Lin Accel (a)	Rot Accel (α)	Rot Vel (ω)	MPS
HEAD-FBPA-A-1MS-V-1	4.6	246.7	4.6	3.2%
HEAD-FBPA-A-1MS-V-2	4.2	270.9	3.4	
HEAD-FBPA-A-1MS-V-3	4.9	319.5	4.2	
Mean	4.6	279.0	4.1	
SD	0.4	37.1	0.6	

	Lin Accel (a)	Rot Accel (α)	Rot Vel (ω)	MPS
HEAD-RB-C-1MS-1	3.7	441.8	7.8	3.3%
HEAD-RB-C-1MS-2	3.5	329.1	6.3	
HEAD-RB-C-1MS-3	3.5	321.7	6.1	
Mean	3.6	364.2	6.7	
SD	0.1	67.3	0.9	

	Lin Accel (a)	Rot Accel (α)	Rot Vel (ω)	MPS
HEAD-S-C-1MS-1	3.4	388.5	4.5	3.5%
HEAD-S-C-1MS-2	3.3	366.1	3.6	
HEAD-S-C-1MS-3	3.0	480.8	4.9	
Mean	3.2	411.8	4.3	
SD	0.2	60.8	0.7	

	Lin Accel (a)	Rot Accel (α)	Rot Vel (ω)	MPS
HEAD-S-C-5MS-1	53.8	3959.0	20.6	26.9%
HEAD-S-C-5MS-2	51.8	3861.3	18.9	
HEAD-S-C-5MS-3	51.7	3959.4	17.8	
Mean	52.4	3926.6	19.1	
SD	1.2	56.5	1.4	

	Lin Accel (a)	Rot Accel (α)	Rot Vel (ω)	MPS
HEAD-F-C-5MS-1	37.5	2994.9	21.2	26.5%
HEAD-F-C-5MS-2	42.6	1964.7	21.8	
HEAD-F-C-5MS-3	39.7	2940.0	22.5	
Mean	39.9	2633.2	21.8	
SD	2.6	579.6	0.7	

SHOULDER

	Lin Accel (a)	Rot Accel (α)	Rot Vel (ω)	MPS
SHO-S-C-1MS-V-1	5.8	467.3	8.5	6.0%
SHO-S-C-1MS-V-2	4.6	325.9	8.5	
SHO-S-C-1MS-V-3	5.5	419.2	9.3	
Mean	5.3	404.1	8.8	
SD	0.6	71.9	0.5	

	Lin Accel (a)	Rot Accel (α)	Rot Vel (ω)	MPS
SHO-S-C-1MS-NV-1	5.5	415.7	8.2	6.0%
SHO-S-C-1MS-NV-2	5.1	364.1	6.6	
SHO-S-C-1MS-NV-3	5.2	400.7	7.1	
Mean	5.3	393.5	7.3	
SD	0.2	26.5	0.8	

	Lin Accel (a)	Rot Accel (α)	Rot Vel (ω)	MPS
SHO-S-C-3MS-NV-1	15.6	1101.2	18.3	16.0%
SHO-S-C-3MS-NV-2	16.0	1023.9	18.4	
SHO-S-C-3MS-NV-3	16.3	996.5	18.9	

Mean	16.0	1040.5	18.5
SD	0.4	54.3	0.3

	Lin Accel (a)	Rot Accel (α)	Rot Vel (ω)	MPS
SHO-S-C-3MS-V-1	16.6	1022.4	18.0	16.9%
SHO-S-C-3MS-V-2	16.8	996.1	18.5	
SHO-S-C-3MS-V-3	16.8	1007.9	19.2	
Mean	16.7	1008.8	18.6	
SD	0.1	13.2	0.6	

	Lin Accel (a)	Rot Accel (α)	Rot Vel (ω)	MPS
SHO-S-C-5MS-NV-1	27.0	1709.9	24.5	27.0%
SHO-S-C-5MS-NV-2	28.3	1656.6	25.8	
SHO-S-C-5MS-NV-3	27.5	1630.5	25.5	
Mean	27.6	1665.7	25.3	
SD	0.7	40.5	0.7	

	Lin Accel (a)	Rot Accel (α)	Rot Vel (ω)	MPS
SHO-F-C-1MS-NV-1	5.1	430.4	6.9	5.6%
SHO-F-C-1MS-NV-2	5.4	425.9	7.0	
SHO-F-C-1MS-NV-3	5.6	452.5	7.1	
Mean	5.4	436.3	7.0	
SD	0.3	14.2	0.1	

	Lin Accel (a)	Rot Accel (α)	Rot Vel (ω)	MPS
SHO-F-C-3MS-NV-1	15.5	824.7	9.5	14.8%
SHO-F-C-3MS-NV-2	15.4	753.2	9.2	
SHO-F-C-3MS-NV-3	15.4	913.8	9.8	
Mean	15.4	830.6	9.5	
SD	0.1	80.5	0.3	

	Lin Accel (a)	Rot Accel (α)	Rot Vel (ω)	MPS
SHO-F-C-3MS-V-1	13.1	684.4	7.3	12.4%
SHO-F-C-3MS-V-2	13.5	591.0	7.1	
SHO-F-C-3MS-V-3	13.7	786.1	8.9	
Mean	13.4	687.2	7.8	
SD	0.3	97.6	1.0	

	Lin Accel (a)	Rot Accel (α)	Rot Vel (ω)	MPS
SHO-FB-C-1MS-V-1	4.4	307.2	7.1	5.9%
SHO-FB-C-1MS-V-2	5.0	301.9	6.6	
SHO-FB-C-1MS-V-3	5.0	330.3	7.3	
Mean	4.8	313.1	7.0	

SD	0.3	15.1	0.4	

	Lin Accel (a)	Rot Accel (α)	Rot Vel (ω)	MPS
SHO-FB-C-5MS-V-1	24.6	1432.6	25.3	28.7%
SHO-FB-C-5MS-V-2	24.2	1262.4	21.9	
SHO-FB-C-5MS-V-3	23.0	1304.8	23.9	
Mean	23.9	1333.3	23.7	
SD	0.8	88.6	1.7	

	Lin Accel (a)	Rot Accel (α)	Rot Vel (ω)	MPS
SHO-RB-C-1MS-1	5.3	353.9	3.7	5.6%
SHO-RB-C-1MS-2	5.4	379.5	3.7	
SHO-RB-C-1MS-3	5.3	343.5	3.8	
Mean	5.3	359.0	3.7	
SD	0.1	18.5	0.1	

	Lin Accel (a)	Rot Accel (α)	Rot Vel (ω)	MPS
SHO-RBNA-A-3MS-1	12.9	1104.3	17.4	13.8%
SHO-RBNA-A-3MS-2	12.5	1063.8	15.6	
SHO-RBNA-A-3MS-3	12.2	1032.5	15.5	
Mean	12.5	1066.9	16.2	
SD	0.4	36.0	1.1	

	Lin Accel (a)	Rot Accel (α)	Rot Vel (ω)	MPS
SHO-F-B-3MS-NV-1	13.6	1194.4	15.8	13.4%
SHO-F-B-3MS-NV-2	13.1	1217.0	16.5	
SHO-F-B-3MS-NV-3	13.1	1164.3	16.2	
Mean	13.3	1191.9	16.2	
SD	0.3	26.4	0.4	

	Lin Accel (a)	Rot Accel (α)	Rot Vel (ω)	MPS
SHO-F-B-3MS-V-1	10.7	870.8	15.1	12.4%
SHO-F-B-3MS-V-2	11.0	931.8	15.9	
SHO-F-B-3MS-V-3	10.8	1047.9	15.9	
Mean	10.8	950.2	15.6	
SD	0.2	90.0	0.5	

	Lin Accel (a)	Rot Accel (α)	Rot Vel (ω)	MPS
SHO-FBPA-B-5MS-V-1	21.7	1657.1	22.6	22.7%
SHO-FBPA-B-5MS-V-2	21.4	1791.7	24.4	
SHO-FBPA-B-5MS-V-3	21.6	1739.7	26.2	
Mean	21.6	1729.5	24.4	
SD	0.2	67.9	1.8	

	Lin Accel (a)	Rot Accel (α)	Rot Vel (ω)	MPS
SHO-FBPA-A-3MS-V-1	13.8	1057.1	17.0	16.4%
SHO-FBPA-A-3MS-V-2	13.8	1109.0	19.6	
SHO-FBPA-A-3MS-V-3	13.7	1109.3	19.6	
Mean	13.8	1091.8	18.7	
SD	0.1	30.1	1.5	

	Lin Accel (a)	Rot Accel (α)	Rot Vel (ω)	MPS
SHO-CR-1MS-1	3.2	205.2	4.6	2.5%
SHO-CR-1MS-2	2.3	221.5	7.4	
SHO-CR-1MS-3	2.5	162.5	5.5	
Mean	2.7	196.4	5.8	
SD	0.5	30.5	1.4	

	Lin Accel (a)	Rot Accel (α)	Rot Vel (ω)	MPS
SHO-S-A-3MS-V-1	15.1	936.1	14.2	16.0%
SHO-S-A-3MS-V-2	14.9	1060.6	18.2	
SHO-S-A-3MS-V-3	14.8	1023.1	18.1	
Mean	14.9	1006.6	16.8	
SD	0.2	63.9	2.3	

	Lin Accel (a)	Rot Accel (α)	Rot Vel (ω)	MPS
SHO-S-B-3MS-V-1	13.9	863.5	17.4	15.0%
SHO-S-B-3MS-V-2	13.9	863.1	16.3	
SHO-S-B-3MS-V-3	14.1	844.6	16.9	
Mean	14.0	857.1	16.9	
SD	0.1	10.8	0.6	

ELBOW

	Lin Accel (a)	Rot Accel (α)	Rot Vel (ω)	MPS
ELB-F-A-1MS-NV-1	5.0	254.2	4.3	5.2%
ELB-F-A-1MS-NV-2	5.3	247.4	4.1	
ELB-F-A-1MS-NV-3	5.1	211.5	4.2	
Mean	5.1	237.7	4.2	
SD	0.2	22.9	0.1	

	Lin Accel (a)	Rot Accel (α)	Rot Vel (ω)	MPS
ELB-FBPA-A-1MS-V-1	5.3	342.1	5.4	5.3%
ELB-FBPA-A-1MS-V-2	5.4	289.9	2.9	
ELB-FBPA-A-1MS-V-3	5.5	372.6	4.5	

Mean	5.4	334.9	4.3
SD	0.1	41.8	1.3

	Lin Accel (a)	Rot Accel (α)	Rot Vel (ω)	MPS
ELB-RBNA-A-1MS-1	3.6	620.5	10.9	4.0%
ELB-RBNA-A-1MS-2	3.6	579.7	9.8	
ELB-RBNA-A-1MS-3	3.6	614.8	9.9	
Mean	3.6	605.0	10.2	
SD	0.0	22.1	0.6	

	Lin Accel (a)	Rot Accel (α)	Rot Vel (ω)	MPS
ELB-R-A-1MS-1	3.8	276.5	8.6	2.9%
ELB-R-A-1MS-2	4.3	316.1	5.8	
ELB-R-A-1MS-3	4.1	324.1	6.2	
Mean	4.1	305.6	6.9	
SD	0.3	25.5	1.5	

	Lin Accel (a)	Rot Accel (α)	Rot Vel (ω)	MPS
ELB-S-C-1MS-V-1	4.3	272.6	5.5	4.9%
ELB-S-C-1MS-V-2	4.5	259.9	5.1	
ELB-S-C-1MS-V-3	4.8	255.3	4.6	
Mean	4.5	262.6	5.1	
SD	0.3	9.0	0.5	

	Lin Accel (a)	Rot Accel (α)	Rot Vel (ω)	MPS
ELB-S-B-1MS-NV-1	3.4	274.9	5.8	3.7%
ELB-S-B-1MS-NV-2	3.4	262.5	5.4	
ELB-S-B-1MS-NV-3	3.8	325.7	6.5	
Mean	3.5	287.7	5.9	
SD	0.2	33.5	0.6	

	Lin Accel (a)	Rot Accel (α)	Rot Vel (ω)	MPS
ELB-RBNA-B-1MS-1	3.9	307.8	3.6	4.0%
ELB-RBNA-B-1MS-2	4.1	361.6	4.8	
ELB-RBNA-B-1MS-3	4.3	349.0	3.9	
Mean	4.1	339.5	4.1	
SD	0.2	28.1	0.6	

	Lin Accel (a)	Rot Accel (α)	Rot Vel (ω)	MPS
ELB-FBPA-B-1MS-V-1	2.3	281.4	9.0	2.8%
ELB-FBPA-B-1MS-V-2	2.7	267.6	8.8	

ELB-FBPA-B-1MS-V-3	2.6	286.2	8.6
Mean	2.5	278.4	8.8
SD	0.2	9.7	0.2

	Lin Accel (a)	Rot Accel (α)	Rot Vel (ω)	MPS
ELB-F-B-1MS-NV-1	4.6	212.0	2.4	
ELB-F-B-1MS-NV-2	4.8	237.3	2.8	3.9%
ELB-F-B-1MS-NV-3	4.9	240.5	3.3	
Mean	4.8	229.9	2.8	
SD	0.2	15.6	0.5	

	Lin Accel (a)	Rot Accel (α)	Rot Vel (ω)	MPS
ELB-FBPA-A-3MS-V-1	13.3	1334.0	18.5	13.3%
ELB-FBPA-A-3MS-V-2	14.2	1667.8	20.6	
ELB-FBPA-A-3MS-V-3	14.6	1434.9	19.9	
Mean	14.0	1478.9	19.7	
SD	0.7	171.2	1.1	

	Lin Accel (a)	Rot Accel (α)	Rot Vel (ω)	MPS
ELB-RBNA-A-3MS-1	13.1	2451.5	23.6	13.2%
ELB-RBNA-A-3MS-2	12.5	2195.9	21.2	
ELB-RBNA-A-3MS-3	12.8	2339.0	21.4	
Mean	12.8	2328.8	22.1	
SD	0.3	128.1	1.3	

	Lin Accel (a)	Rot Accel (α)	Rot Vel (ω)	MPS
ELB-S-A-3MS-1	20.7	1607.1	15.9	12.8%
ELB-S-A-3MS-2	20.2	1531.1	14.1	
ELB-S-A-3MS-3	19.7	1512.1	14.6	
Mean	20.2	1550.1	14.9	
SD	0.5	50.3	0.9	

	Lin Accel (a)	Rot Accel (α)	Rot Vel (ω)	MPS
ELB-FBPA-B-3MS-V-1	9.2	891.2	19.9	10.1%
ELB-FBPA-B-3MS-V-2	10.4	1027.2	20.0	
ELB-FBPA-B-3MS-V-3	10.5	1044.6	19.5	
Mean	10.0	987.7	19.8	
SD	0.7	84.0	0.3	

	Lin Accel (a)	Rot Accel (α)	Rot Vel (ω)	MPS
ELB-FB-C-3MS-NV-1	20.7	1763.5	12.2	21.8%
ELB-FB-C-3MS-NV-2	21.1	1823.0	12.4	

ELB-FB-C-3MS-NV-3	21.3	1810.8	12.2
Mean	21.0	1799.1	12.3
SD	0.3	31.4	0.1

	Lin Accel (a)	Rot Accel (α)	Rot Vel (ω)	MPS
ELB-F-B-3MS-NV-1	16.4	1108.3	10.6	15.6%
ELB-F-B-3MS-NV-2	16.2	1104.8	10.7	
ELB-F-B-3MS-NV-3	16.6	1090.3	10.4	
Mean	16.4	1101.1	10.6	
SD	0.2	9.5	0.2	

	Lin Accel (a)	Rot Accel (α)	Rot Vel (ω)	MPS
ELB-F-B-3MS-V-1	15.4	982.3	11.0	14.8%
ELB-F-B-3MS-V-2	15.8	1062.6	11.6	
ELB-F-B-3MS-V-3	16.9	1026.3	12.3	
Mean	16.0	1023.7	11.6	
SD	0.8	40.2	0.7	

	Lin Accel (a)	Rot Accel (α)	Rot Vel (ω)	MPS
ELB-F-C-3MS-V-1	17.7	1208.9	12.5	16.0%
ELB-F-C-3MS-V-2	17.4	1240.6	13.0	
ELB-F-C-3MS-V-3	16.8	1088.5	12.1	
Mean	17.3	1179.3	12.5	
SD	0.5	80.2	0.5	

	Lin Accel (a)	Rot Accel (α)	Rot Vel (ω)	MPS
ELB-S-B-3MS-V-1	12.9	1224.5	15.2	11.4%
ELB-S-B-3MS-V-2	13.8	1284.8	16.8	
ELB-S-B-3MS-V-3	13.6	1213.4	16.7	
Mean	13.4	1240.9	16.2	
SD	0.5	38.4	0.9	

	Lin Accel (a)	Rot Accel (α)	Rot Vel (ω)	MPS
ELB-S-B-3MS-NV-1	14.7	1317.6	16.4	13.3%
ELB-S-B-3MS-NV-2	14.8	1289.6	15.5	
ELB-S-B-3MS-NV-3	14.7	1288.1	15.0	
Mean	14.7	1298.4	15.6	
SD	0.1	16.6	0.7	

	Lin Accel (a)	Rot Accel (α)	Rot Vel (ω)	MPS
ELB-S-C-3MS-NV-1	19.3	1237.6	15.3	17.3%
ELB-S-C-3MS-NV-2	18.5	1218.3	15.6	
ELB-S-C-3MS-NV-3	19.0	1237.6	16.2	
Mean	18.9	1231.2	15.7	
SD	0.4	11.1	0.5	

	Lin Accel (a)	Rot Accel (α)	Rot Vel (ω)	MPS
ELB-S-C-3MS-V-1	19.7	1474.0	15.5	17.5%
ELB-S-C-3MS-V-2	19.7	1475.1	14.9	
ELB-S-C-3MS-V-3	20.1	1473.0	14.9	
Mean	19.8	1474.0	15.1	
SD	0.2	1.1	0.3	

	Lin Accel (a)	Rot Accel (α)	Rot Vel (ω)	MPS
ELB-S-C-5MS-V-1	37.2	3039.4	23.1	30.3%
ELB-S-C-5MS-V-2	39.9	3311.6	24.1	
ELB-S-C-5MS-V-3	39.0	2969.2	23.1	
Mean	38.7	3106.7	23.4	
SD	1.4	180.9	0.6	

	Lin Accel (a)	Rot Accel (α)	Rot Vel (ω)	MPS
ELB-S-C-5MS-NV-1	41.9	3203.9	24.3	32.4%
ELB-S-C-5MS-NV-2	43.1	3323.8	24.6	
ELB-S-C-5MS-NV-3	43.1	3215.0	24.5	
Mean	42.7	3247.6	24.5	
SD	0.7	66.3	0.2	

GLOVE

	Lin Accel (a)	Rot Accel (α)	Rot Vel (ω)	MPS
GLOVE-F-B-3MS-NV-1	3.6	381.5	5.8	3.6%
GLOVE-F-B-3MS-NV-2	3.7	309.3	6.5	
GLOVE-F-B-3MS-NV-3	3.5	404.8	6.9	
Mean	3.6	365.2	6.4	
SD	0.1	49.8	0.6	

	Lin Accel (a)	Rot Accel (α)	Rot Vel (ω)	MPS
GLOVE-FB-C-3MS-NV-1	2.6	394.8	6.7	3.9%
GLOVE-FB-C-3MS-NV-2	2.7	370.9	5.3	
GLOVE-FB-C-3MS-NV-3	2.5	419.3	6.7	
Mean	2.6	395.0	6.2	
SD	0.1	24.2	0.8	

	Lin Accel (a)	Rot Accel (α)	Rot Vel (ω)	MPS
GLOVE-S-A-3MS-V-1	3.1	305.3	3.5	4.0%
GLOVE-S-A-3MS-V-2	3.3	338.3	4.7	
GLOVE-S-A-3MS-V-3	3.2	332.3	5.3	

Mean	3.2	325.3	4.5	
SD	0.1	17.6	0.9	

PUNCH

	Lin Accel (a)	Rot Accel (α)	Rot Vel (ω)	MPS
PUNCH-F-B-1MS-NV-1	4.5	253.3	4.8	4.1%
PUNCH-F-B-1MS-NV-2	3.3	236.3	5.2	
PUNCH-F-B-1MS-NV-3	4.0	220.8	4.3	
Mean	3.9	236.8	4.8	
SD	0.6	16.3	0.5	

	Lin Accel (a)	Rot Accel (α)	Rot Vel (ω)	MPS
PUNCH-F-C-1MS-V-1	2.2	226.3	6.7	2.7%
PUNCH-F-C-1MS-V-2	2.3	153.6	4.1	
PUNCH-F-C-1MS-V-3	2.2	157.1	3.8	
Mean	2.2	179.0	4.9	
SD	0.1	41.0	1.6	

	Lin Accel (a)	Rot Accel (α)	Rot Vel (ω)	MPS
PUNCH-S-C-1MS-V-1	3.9	316.0	8.2	4.3%
PUNCH-S-C-1MS-V-2	3.8	278.4	7.2	
PUNCH-S-C-1MS-V-3	4.0	293.9	6.8	
Mean	3.9	296.1	7.4	
SD	0.1	18.9	0.7	

	Lin Accel (a)	Rot Accel (α)	Rot Vel (ω)	MPS
PUNCH-R-B-1MS-NV-1	3.6	328.8	8.4	3.7%
PUNCH-R-B-1MS-NV-2	3.6	336.0	7.5	
PUNCH-R-B-1MS-NV-3	3.5	270.0	5.9	
Mean	3.6	311.6	7.3	
SD	0.1	36.2	1.3	

	Lin Accel (a)	Rot Accel (α)	Rot Vel (ω)	MPS
PUNCH-R-B-3MS-NV-1	15.8	837.2	16.5	11.8%
PUNCH-R-B-3MS-NV-2	15.5	862.0	16.0	
PUNCH-R-B-3MS-NV-3	15.4	914.5	15.9	
Mean	15.6	871.2	16.1	
SD	0.2	39.5	0.3	

	Lin Accel (a)	Rot Accel (α)	Rot Vel (ω)	MPS

PUNCH-R-C-3MS-NV-1	14.9	810.7	13.8	11.9%
PUNCH-R-C-3MS-NV-2	14.8	884.1	14.4	
PUNCH-R-C-3MS-NV-3	14.9	923.0	14.3	
Mean	14.9	872.6	14.2	
SD	0.1	57.0	0.3	

	Lin Accel (a)	Rot Accel (α)	Rot Vel (ω)	MPS
PUNCH-FB-C-3MS-NV-1	14.7	1073.9	9.6	15.6%
PUNCH-FB-C-3MS-NV-2	15.6	1145.1	11.4	
PUNCH-FB-C-3MS-NV-3	15.4	1116.1	11.3	
Mean	15.2	1111.7	10.8	
SD	0.5	35.8	1.0	

MEP

	Lin Accel (a)	Rot Accel (α)	Rot Vel (ω)	MPS
MEP-RB-C-3MS-V-1	59.2	3429.9	15.2	34.3%
MEP-RB-C-3MS-V-2	56.7	3068.2	13.2	
MEP-RB-C-3MS-V-3	65.4	4004.9	16.0	
Mean	60.4	3501.0	14.8	
SD	4.5	472.4	1.4	

	Lin Accel (a)	Rot Accel (α)	Rot Vel (ω)	MPS
MEP-RB-C-3MS-NV-1	61.5	2778.2	14.2	36.1%
MEP-RB-C-3MS-NV-2	69.1	3673.2	15.5	
MEP-RB-C-3MS-NV-3	66.0	3249.0	14.4	
Mean	65.5	3233.5	14.7	
SD	3.8	447.7	0.7	