

Concussions in the National Hockey League (NHL): The Video Analysis Project

by

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A thesis submitted in conformity with the requirements
for the degree of Doctoral of Philosophy
Graduate Department of Rehabilitation Science
University of Toronto

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2011

Abstract

Hockey is a popular sport, and at its highest levels, it is a complex contact game characterized by physical strength, speed, and skill. The interaction of these characteristics contributes to the inherent risk of injury athletes must face while playing. Among hockey injuries, concussions are one of the most commonly sustained by athletes across all levels of play and age groups. Significant public attention, combined with poorly understood long-term effects, indicates the importance of tangible preventive strategies. The main goal of this thesis was to understand, through video analysis, how playing characteristics and mechanism of injury contribute to concussions in the National Hockey League (NHL). In the first study, the development and validation of an observational recording tool used to code and analyze NHL concussions observed via video analysis was described. The second study attempted to synthesize the description of players' characteristics, antecedent events, and contextual variables associated with events leading to concussion at the NHL level. Several specific risk factors for concussion in NHL players were identified, including position, body size,

specific locations on the ice, and particular situations based on a player's position. The final study systematically analyzed how concussions occur to identify potential pattern(s) of concussions. A common specific injury mechanism characterized by player-to-player contact and resulting in contact to the head by the shoulder, elbow, or gloves, was also identified. When the principal mechanism was refined further, several important characteristics were discernable: (i) contact was often to the lateral aspect of the head; (ii) the player who suffered a concussion was often not in possession of the puck; and (iii) no penalty was called on the play. Collectively, these studies served to address gaps in the literature; the implications for informing prevention and management strategies are also discussed.

Acknowledgments

It is a pleasure to thank the many people who made this thesis possible.

It is with sincere appreciation that I acknowledge my supervisors, Dr. Paul Comper and Dr. Angela Colantonio. It is difficult to overstate my gratitude to Dr. Paul Comper. As a supervisor, he provided encouragement, sound advice, high-quality teaching, and good company. I thank Dr. Angela Colantonio for her support and guidance while pursuing my academic studies.

I wish to thank the members of the National Hockey League (NHL) and the National Hockey League Players' Association (NHLPA) who provided assistance, support, and feedback throughout the research project. I am especially grateful to all of the members of the Concussion Working Group.

A very special thanks my family and friends for their support. In particular, I wish to thank my parents, Susanne Hutchison and Ron Hutchison, for their unconditional love, teachings, and support that has made this piece of my life possible.

In conclusion, I recognize that this research would not have been possible without the support and financial assistance of the University of Toronto, the University of Toronto Graduate Department of Rehabilitation Science, the Ontario Neurotrauma Foundation, and the Dr. Pashby Sports Safety Fund, and express my gratitude to those agencies.

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1 Chapter 1

Introduction

Ice Hockey (“hockey”) is a complex contact sport involving the combination of speed, agility, diverse physiological demands, and technical mastery. With respect to speed, skating velocities up to 45 km/hour have been reported, with puck velocities occasionally exceeding 160 km/h.¹ Players must execute their abilities and skills within an enclosed area containing hard surfaces and obstacles such as boards and surrounding glass, ice, goal nets, officials and perhaps, most importantly, their opponents. These are a few of the features that attract many young athletes to the sport. In Canada, hockey is one of the most popular sports for young athletes; in 2008, 550,000 players under the age of 19 were registered.² Hockey participation in the United States (US) also appears to be on the rise; in 2008, 345,000 youth players were registered.³ At the same time, the interaction among the characteristics that appeal to many hockey players contributes to the significant risk of injury athletes must face.

1.1 Hockey Injuries

Historically, the majority of severe injuries in hockey occurred as a result of head trauma (including face, scalp, and brain injuries),⁴⁻¹¹ mainly attributable to

a lack of quality protective equipment and regulations to protect the head and face region.¹¹ In Canada, it was not until 1978 that amateur hockey players were required to wear helmets approved by a technical standards committee.¹² Hockey helmets were developed to protect against focal-type head injuries that could result in skull fractures and/or additional intracranial pathology such as subdural or epidural hematoma. When worn correctly – that is, properly fitted and with a chin strap – hockey helmets have performed well for their intended purpose.¹²⁻¹⁷ However, since helmets do not prevent ocular, facial or dental injuries, further protective equipment has been developed. An injury to Greg Neeld, a junior player with the Toronto Malboros who lost an eye after a high-sticking incident in 1973, led to an investigation on the incidence of eye injuries in hockey.⁹ It was reported that an alarming 43 legally blind eyes due to hockey injuries in Canada occurred during the 1975/75 season.⁹ At this time, the issue was referred to as an “epidemic” and advocacy for the requirement of all amateur hockey players to wear eye protection was led by Toronto physician Dr. Tom Pashby.⁹ The helmet and full face shield are effective at preventing specific types of injuries. While the introduction of basic head protection offered by the hockey helmet greatly reduced the incidence of focal head injuries and related problems, the addition of the full face shield to the hockey helmet improved players' eye protection to the extent that the number of blind eyes has become non-existent when approved full face shields are properly used.^{12, 18, 19}

Despite advances in equipment technology and player protection, serious injuries in hockey occur nonetheless. Common injuries in the modern game of hockey played at the elite levels (where body checking is allowed and full face

shields are not mandatory) include lacerations,^{20, 21} shoulder trauma (glenohumeral or acromioclavicular joint), knee injuries (often medial collateral ligament), and ankle sprains.²¹⁻²³ Muscle Strains are also frequent and are more common to the groin and abdominal area; such injuries are often associated with quick acceleration and deceleration during skating, resulting in the disruption of the muscle-tendon units.^{1, 24, 25} For the young athlete, hockey has been reported to have one of the highest injury rates among all sports.²⁶ Similar to their elite counterparts, younger, amateur level hockey players most frequently suffer soft tissue injuries to the shoulder and knee region.²⁷⁻²⁹ However, a thorough understanding of the frequency of specific injuries and risk factors in youth hockey has been difficult to determine because of the impact and inconsistency of body-checking rules. For a number of years, governing bodies have debated the age at which body-checking should be introduced and this has resulted in different regulations across the Canada and United States.³⁰⁻³² Body checking has been associated with an increased risk of injury,^{28, 33, 34} and a number of studies have found that the risk has increased with increasing skill level across age groups.^{21, 35-37} However, to date, findings regarding most risk factors for injury in youth hockey remain inconclusive.²⁹

The research community has responded to the inherent risks of injury in hockey with a significant increase of effort in the area of injury surveillance. Such research aims to capture, measure, and determine risk factors associated with common injuries in hockey. However, surveillance of sport-related injuries has suffered from methodological inconsistencies surrounding injury definitions and recording methods, combined with a lack of accurate exposure data.³⁸

1.2 Concussions in hockey

Among hockey injuries, concussions are one of the most common injuries sustained by athletes across all levels of play and age groups.^{15, 32, 39-44} The word "concussion" is derived from the Latin verb *concutere*, which means "to shake"; it refers to a clashing together, an agitation, or disturbance, or shock of impact.⁴⁵⁻⁴⁷ Historical accounts suggest that at the end of the first millennium, Rhazes (AD 850-?), an Arabic physician, was the first to clearly describe the entity of concussion and he clearly appreciated that concussion could occur independently of any gross pathology or skull fracture.⁴⁶ Rhazes also made the distinction between concussion as an abnormal physiologic state rather than severe brain injury or as a generic descriptor of brain injury.⁴⁶ However, French military surgeon Ambroise Paré (1510–1590) is often credited with introducing the name concussion as he popularized the term when he wrote of the "concussion, *commotio cerebri* or shaking of the brain".⁴⁷ Simply put, concussion is used to describe both a particular clinical state and the events that bring about that clinical state and there exists extensive literature on both its use and evolving characteristics; however, controversy remains regarding the commonly accepted definitions.^{45, 46} It is now well accepted by most that a concussion is a type of mild traumatic brain injury, though a variety of definitions have been offered.¹²³ For the purposes of this thesis, the American Academy of

¹ Concussion in Sport consensus statement defines concussion as a "complex pathophysiological process affecting the brain, induced by traumatic biomechanical forces" (Zurich, 2008).

Neurology's definition of concussion has been adopted; a concussion is defined as a traumatically-induced alteration of mental status that may or may not involve a loss of consciousness.⁴⁸

1.3 Signs and symptoms of concussion

If a concussion is suspected, the acute assessment by a first responder includes the clinical evaluation of neurological signs and symptoms, ideally using a standardized assessment protocol.⁴⁹⁻⁵¹ A neurological 'sign' is a marked abnormality of function or structure observed in the injured person by a clinician, whereas a 'symptom' is a manifestation of disorder or abnormality reported by the injured person. The most obvious signs of concussion include a loss of consciousness, amnesia for events around the injury, confusion, slow response to questions, and functional memory impairment.⁵²⁻⁵⁵ Signs of concussion frequently include poor coordination and/or balance, slurred speech, vacant stare/glassy eyed expression, and other signs of neurological impairment.^{52, 54-60} Athletes may report zero to numerous subjective symptoms, most frequently headache, dizziness, fatigue, sleep disturbance, nausea, and cognitive

² The Centers for Disease Control and Prevention defines concussion as: a type of traumatic brain injury, or TBI, caused by a bump, blow, or jolt to the head that can change the way your brain normally works. Concussions can also occur from a fall or blow to the body that causes the head and brain to move quickly back and forth.

³ Department of Veterans Affairs (VA) / Department of Defense (DoD): a traumatically induced structural injury and/or physiological disruption of brain function as a result of an external force that is indicated by new onset or worsening of manifestation of disorder.

problems.^{52, 54, 55, 57-63} Conventional static macroscopic neuroimaging techniques (e.g., CT or MRI) are typically unremarkable with concussion and are used only if a more severe brain injury is suspected.^{52, 54, 55} Importantly, although an individual may display transient neurological signs following a concussion, the presence of persistent signs may signal a more serious underlying neurological problem warranting clinical attention, in which case the diagnosis of concussion may be superseded by ICD-10 nomenclature such as cerebral "contusion" or, if there is resultant intracranial bleeding, "hematoma" or "hemorrhage".

Following a suspected concussion, if an athlete displays any signs or reports any symptoms, current management guidelines stipulate that the player be removed from play and not return to play the same day.⁵⁵ Current consensus return-to-play guidelines recommend athletes wait until asymptomatic at rest, then proceed through a stepwise exercise progression, and only proceed to the next level if asymptomatic at the current level.⁵⁵ Generally, completion of exercise progression will take an athlete approximately one week to proceed through the full rehabilitation protocol once they are asymptomatic at rest and with provocative exercise.⁵⁵

In summary, an athlete diagnosed with a concussion has suffered a neurotrauma from which they may experience debilitating symptoms, but with no persistent neurological signs or positive neuroimaging findings. Management includes minimal intervention, with rest (cognitive and physical) as the initial prescription, followed by gradual progression through exercise provocation to return to play.

The literature suggests that the majority of athletes with concussion (approximately 80%) will make full recoveries in a short time period.^{55, 64} However, concussions are a unique injury because a significantly large proportion of athletes – the remaining 20% who do not quickly recover – experience prolonged duration of symptoms and functional difficulties even though the injury mechanisms may be similar to those who spontaneously recovered in a short time frame.

1.4 Pathophysiology of concussion

An appreciation for the large amount of variability in the time to a full functional recovery following concussion is likely a consequence of the complexity of underlying physiology and other contributing factors (e.g., psychological factors or pre-morbid characteristics). The most recent conceptualization of concussion describes it as a complex phenomenon, involving interconnected pathophysiological/neurophysiological (i.e., cellular and vascular) changes that occur as a multi-layered metabolic cascade.⁶⁵ The primary mechanisms in this model include ionic shifts, abnormal energy metabolism, diminished cerebral blood flow, and abnormal neurotransmission.⁶⁵

It has been suggested that a concussion does not represent a linear spectrum of severity as a similar mechanism can result in vastly different clinical outcomes.⁵² It is likely that there are a number of factors that influence prolonged recovery such as prior history of head injury, biomechanical factors (direction, magnitude, and duration of force), underlying personality

characteristics, anatomical localization, or an as-yet undefined difference that requires a more sophisticated approach to the understanding of this phenomenon.⁵⁵ A recent paper by Benson and colleagues suggested that hockey players who have post-concussion headache, low energy or fatigue, amnesia, and abnormal neurological examination initially may be at risk for lengthier recoveries.⁶⁶

Recent advances in technology have permitted investigators to explore sophisticated approaches in concussion research. Such techniques include functional magnetic resonance imaging (fMRI),⁶⁷⁻⁷⁰ event-related potentials (ERP),⁷¹ diffusion tensor imaging (DTI),^{72, 73} unique biomarkers (S100B),⁷⁴ and indices of mitochondrial-related function by hydrogen nuclear magnetic resonance (H-NMR) spectroscopy^{75, 76} to examine potential correlates of concussive injury and/or recovery. With the use of modern research tools, these approaches will likely lead to an accumulation of knowledge and a better understanding of the cellular and molecular damage associated with concussion.

Although the investigation of novel techniques in concussion research has increased in recent years, ostensibly to identify pathological 'signs' associated with subjective symptoms and recovery patterns, the overall body of literature in this area indicates that most of the studies in sports concussion undertaken in the past 20 years involve assessing the clinical utility of neuropsychological (NP) testing to determine recovery or normalization.⁶⁴

1.5 Neuropsychological testing for concussion

The use of NP testing to objectively measure sports concussion-related impairments and recovery was pioneered by Barth and colleagues almost thirty years ago. Barth's original approach was simple, logical, and efficient: athletes were tested before their competitive seasons and those who sustained concussions were also assessed afterwards.⁶⁴ The difference between 'baseline' and post-injury scores was then analyzed.⁷⁷ Athletes were recognized to be a unique population and amenable to objective study as they were characterized as motivated, non-litigious, and generally healthy, which in turn suggested that any post-trauma subjective symptoms or objectively-measured deficits could logically be attributed to the concussive injury. The early history of NP assessment focused on the development of brief paper-and-pencil test batteries for use in athlete populations. More recently, the widespread implementation of computerized neuropsychological test protocols has offered the prospect of concussion assessment with much greater sensitivity than possible even a decade ago.⁶⁴

Overall, NP research generally supports the notion that sports-related concussion temporarily disrupts cognitive functioning, and often resolves within 7-10 days, which corresponds to the typical time course of symptom recovery.^{55,}
⁶⁴ However, recent research using brain metabolism and physiological markers has found that the duration of physiological recovery after concussion may extend longer than the observed clinical recovery.^{60, 78} Ultimately, these findings have major implications in management strategies, particularly with regard to

preventing recurrent concussions and also mitigating the risk of possible catastrophic outcome in sports.⁶⁰

1.6 Injury Prevention

Understanding *what* happens following concussion is important because it speaks to the timely, appropriate, and prudent management of the injury. It is equally important to understand *how* concussions happen, as it will inform future prevention strategies. Particularly over the last few years, there has been heightened concern of the long-term effects of concussions. Epidemiological research that has focused on retired professional football players has reported an association between sport-related concussions and cognitive impairments later in life.^{79, 80} Also, research that has identified structural abnormalities in former professional athletes, has received significant attention, both academic and public.⁸¹ Collectively, the preliminary research of the long-term effects of concussions warrants efforts to develop tangible preventive strategies.

In order to implement effective preventive strategies, a detailed description of injury mechanisms is necessary. Unfortunately, determining the mechanism of concussion is often difficult to discern, as eyewitness accounts – especially if these are based on injured players' memories of events - can be unreliable. One of the most reliable and efficient records of how an injury occurred is the use of archived video imaging. The practical value of video replay is that it affords a researcher or clinician the opportunity to thoroughly document and describe events typically leading up to injury using sport specific terms. Understanding

the precise sequences leading to sports injuries can therefore objectively inform prevention strategies.

1.7 Previous use of video analysis in sport

The widespread availability of video replay technology allows the viewer an opportunity to look back in time objectively. The practical value of video replay has been known for decades, and coaches in various sports have used video replay for technical and strategic purposes. The use of video replay to understand injury mechanisms in sport is not new; previous attempts to conduct systematic video analyses in other sports include a study published almost 20 years ago on cervical spine injuries in rugby players.⁸² The authors of that study found most of the injuries occurred in the “ruck” and “maul” situations and that such injuries were caused by so-called “irresponsible actions”.⁸² Moreover, results indicated that the rules of the game were not being enforced, and that stricter officiating might prevent similar injuries.⁸² Video analysis was also used in an Alpine skiing context to describe the so-called “phantom foot” injury mechanism as a typical movement pattern associated with certain orthopedic injuries. In the end, the authors used this information to produce a video-based awareness training program, in which skiers were instructed on how to avoid dangerous behaviour.⁸³ It was reported that the program reduced the rate of anterior cruciate ligament (ACL) injuries by 62% among professional skiing instructors and ski patrols.⁸³ In a study involving soccer players, investigators found that the most common injury mechanism leading to head injury involved

elbow-to-head contact during heading duels. This led to the authors' suggestion for stricter rule enforcement and/or rule changes that could lead to reduced risk.⁸⁴

1.8 Systematic video analysis in hockey

Specific to hockey, a pilot study involving the video analysis of concussion mechanisms in National Hockey League (NHL) players was undertaken by Dryden, Meeuwisse, and Benson a decade ago.⁸⁵ However, the effort was undertaken when VHS tapes were still the principal recording medium, the use of which proved to be too time consuming and often of poor quality, hence ineffective for the researchers' purposes. Advances in technology have fostered a digital media environment in which records from every NHL regular season and playoff game are now compiled, accessible and available for careful review, lending to easier analysis of the antecedent events and mechanisms of all types of injury, including concussions. Modern digital high definition video technology provides an investigator with a convenient medium with which to review and play back records with precision and slow motion/step-frame. In addition, it is expected that digital video records of NHL games in recent years will be of good to excellent quality, with multiple camera angles and perspectives.

Although the analysis of digital video is promising, affording the investigator a window to understand the antecedent events and mechanisms of concussions, a strong potential of viewer bias exists nonetheless. Viewer bias can occur when the investigator unintentionally favours a nonrandom, selective approach to analysis, consequently affecting the outcome; this may threaten the

validity of results when incorrect relationships between causal factors and observed outcomes are drawn. Therefore, it is incumbent on researchers to recognize and reduce this potential source of error, using appropriate methodology. If a valid and reliable objective recording tool was available, it would permit the quantification and analysis of concussions via digital video analysis.

1.9 Rationale

Hockey appeals to many young athletes, yet has one of the highest rates of concussion of any sport.²⁶ At the professional level, the NHL has been tracking and studying concussions since 1997, and has developed a comprehensive strategy to document, carefully assess, and monitor recovery of their athletes. Not only is the NHL an ideal laboratory to understand *what* happens following concussion, but affords investigators to understand *how* concussions happen. From a research perspective, there is a vast amount of video information available for careful review, which lends easily to an analysis of the antecedent events and mechanisms of all types of injuries, including concussions.

The main goal of this thesis is to understand how NHL concussions occur, and to inform prevention and management strategies. The project provides the opportunity to investigate both players' and public concerns about concussions in a collaborative research framework involving a large sample of video recorded information of professional hockey players, and to make decisions regarding

prevention and management strategies informed by science. It is expected that the analyses will enhance concussion prevention and management strategies in the NHL, as well as minor hockey and potentially other sports. Possible intervention strategies arising from this research could include awareness and education initiatives, rule changes, and equipment re-design strategies.

1.10 Objectives

In order to accomplish the main goal of the thesis, three specific objectives were proposed:

1. To develop and test an objective recording tool that would permit the numerical coding and analysis of NHL concussions via video analysis. [Chapter 2].
2. To synthesize the description of players' physical characteristics, antecedent events, and contextual variables associated with events leading to concussion at the NHL level. [Chapter 3].
3. To systematically analyze how concussions occur at the NHL level to identify potential pattern(s) of concussions. [Chapter 4].

Chapters two through four are structured as independent journal articles and correspond to each of the above stated objectives. The final chapter will include the discussion of the thesis in its entirety. Given this organization, some material is repeated at the beginning of each chapter.

2 Chapter 2

Heads Up Checklist: an observational recording tool to code and describe concussions in hockey

2.1 Introduction

Participation in hockey has an inherent risk for injury: It is a sport characterized by speed and physicality, played by highly skilled individuals within an enclosed venue. The frequency and types of injuries in hockey vary at different levels of play;³⁹ however, there is particular concern for the frequency of concussion across all levels of play.^{15, 32, 39, 40} Concussion is a traumatically-induced alteration of mental status that may or may not involve a loss of consciousness.⁴⁸ This injury is not exclusive to the hockey arena and affects a number of sports to varying degrees. The incidence of sport-related concussions has likely contributed to the large increase in the number of scientific publications focusing on this particular injury.⁸⁶ At the same time, health professionals, researchers, and amateur and professional organizations have consolidated efforts to address this health issue through management, education, and scientific endeavors. In 2001, an international symposium was held to address issues and problems of concussions in sport. A formal consensus statement was

established by the symposium participants in 2002, designed to inform those involved in the care of athletes with concussions.⁵² Since the first consensus meeting, two additional consensus conferences have produced a further conceptual understanding of concussions in sport.^{54, 55}

According to the literature, concussed athletes may report few or many subjective symptoms, most frequently headache, dizziness, fatigue, sleep disturbance, nausea, and cognitive problems.^{57-59, 61} Current objective measures of cognitive abilities – neuropsychological test scores – typically normalize on average between 7 – 10 days,^{59, 87-91} which largely corresponds to the typical time course of symptom recovery.^{55, 64} The majority of concussed athletes appear to make unremarkable recoveries in a relatively short time frame with minimal residual effects. Nevertheless, a subset of athletes may endure symptoms and functional difficulties for weeks or even months; and to date, the underlying reasons for those protracted recoveries are not well understood. Potentially of greater concern is the growing body of evidence examining the association of sport concussions and cognitive impairments later in life. Much of this preliminary research has been epidemiological in nature and focused on retired professional football players;^{79, 80} however, more recently, identification of structural abnormalities, formally referred to as chronic traumatic encephalopathy,⁸¹ has heightened public concern.

Given the potential long-term consequences and the predictable frequency with which concussions occur in hockey,^{90, 92-94} it behooves all stakeholders to develop strategies for prevention. However, in order to

implement effective preventive strategies, an understanding of the situational context and injury mechanisms is necessary. Unfortunately, the mechanism of concussion is often difficult to discern; eyewitness accounts – especially if these are based on injured players' memories of events – can be extremely unreliable.

The widespread availability of video replay technology allows the viewer an opportunity to look back in time objectively. The practical value of video replay (which in the past consisted of magnetic tape media, but currently involves digital video recordings) has been known for decades: coaches in various sports have used video replay for technical and strategic purposes. More recently, the technology has been incorporated into games to assist officials (i.e., whether a goal has been scored, if an infraction occurred, or whether a tennis serve is “out” or “in”, etc.). However, the same approach can be used to systematically analyze injury mechanisms. Additionally, video analysis also affords a researcher or clinician the opportunity to thoroughly document and describe events typically leading up to injury using sport specific terms. Understanding the precise sequences leading to sports injuries can therefore objectively inform prevention strategies.

The use of video replays to understand injury mechanisms in sport is not new; almost 20 years ago a study examined cervical spine injuries in rugby players using video analysis.⁸² The authors found that most injuries occurred in the “ruck” and “maul” situations, and that such injuries were caused by so-called “irresponsible actions”. Investigators have also attempted to use video analysis of injuries in other sports including alpine skiing⁸³ and soccer.⁹⁵

More recently, with the relatively low cost and accessibility of digital video technology, combined with the high quality, it is common practice for many sports to provide video coverage, even at lower levels of play. Specific to professional hockey, National Hockey League (NHL) games are frequently televised, providing a wealth of digitally recorded information, even for avid fans and casual spectators. At the same time, the league independently monitors, catalogues, and archives video footage from all games. From a research perspective, the information is available for careful review, which lends easily to an analysis of the antecedent events and mechanisms of all types of injury, including concussions.

Although the analysis of digital video records is promising for critical analysis of the antecedent events and mechanisms of concussion, the potential for viewer bias still exists. Viewer bias can occur when the investigator unintentionally favours a nonrandom, selective approach to analysis, consequently affecting the outcome; this may threaten the validity of results when incorrect relationships between causal factors and observed outcomes are drawn. Thus, it is incumbent on researchers to implement a systematic approach to reduce this potential source of error.

With this in mind, this paper describes the development and assessment of the utility of an objective recording tool known as the Heads Up Checklist (HUC) for coding and analysis of NHL concussions via video records. Specifically, it will summarize and discuss two related studies, both of which aimed to determine whether independent raters using the HUC agree with a high

degree of confidence (reliability) on the appropriately identified constructs (validity).

2.2 Methods

The NHL currently has a comprehensive injury surveillance strategy in place, with oversight of policy and prevention undertaken by the Health Management Panel (HMP). In this context, team physicians diagnose and are required to report player injuries to the league's central injury surveillance system. The Concussion Working Group (CWG) is a subcommittee of the HMP; it is comprised of allied health care advisors and other professionals drawn from both the league and the NHL Players' Association (NHLPA). The CWG has been tracking and studying NHL player concussions since 1997-98. Presently, the NHL concussion program operates as a hybrid clinical care/research effort. The broad aims of the program include the examination of issues and protocols related to post injury management and evaluation, return to play and ultimately, concussion prevention.

In the context of the current research effort, following a detailed proposal to both the league and players' union, the investigators (MH and PC) were granted access to the extensive digital video image archives maintained by NHL Hockey Operations. Video records of injuries medically diagnosed as concussions were made available for coding and analysis. Additional descriptive information such as date of injury, period, and known characteristics of the players (i.e., age, height, weight, etc.) were also provided. The research ethics review board of the University of Toronto approved the study.

Study 1 included four raters (two expert and two naïve) who viewed recorded digital video content of concussion-events. Naïve raters were defined as individuals with limited experience playing or coaching hockey at a competitive level. Expert raters were defined as individuals with several years of experience playing or coaching hockey at a competitive level. After viewing each of 25 events chosen randomly from the pool of events for the 2006-07 NHL season, each rater independently completed the Heads Up Checklist (HUC) version 1.1. When all events had been viewed, aggregate data with respect to inter-rater agreement were analyzed. Following this preliminary assessment, the HUC was revised for the second study, and the larger pool of concussion events was analyzed.

The second study required two expert raters to view – in a randomized order – the remaining concussion events (N = 174) from the 2006-2007 season, up to and including events ending on December 31, 2009 (i.e., for three and a half NHL regular seasons) and complete a separate HUC for each event. For both studies, raters viewed each event using Quicktime Player Pro Version 7.6.6 software resident on an Apple MacBook Pro 4.1 (operating software Mac OS X Version 10.5.8).⁹⁶ Each category of the HUC (version 1.2) was completed for each distinct concussion event. Raters were allowed to view the event as many times as required, at any “playback speed” deemed necessary to complete all categories on the HUC.

2.2.1 Heads Up Checklist (HUC)

An earlier version of the HUC (v 1.0) was developed as part of a pilot project examining body contacts at the Canadian Interuniversity Sport (CIS) level.⁹⁷ However, the inconsistent and poor quality of video images (i.e., magnetic tape media) during the original study period rendered the project ineffective for its original purposes. More recently, in collaboration with hockey experts, including NHL/NHLPA Concussion Working Group (CWG) members, the HUC was re-designed for an NHL study. The HUC (v 1.1) was developed to permit a standardized framework to provide a person viewing digital video images with a consistent way of coding and accounting for the majority of circumstances and mechanisms leading to concussion.

As of July 2008, the HUC (v 1.1) consisted of 15 general factors organized under three broad sections: (1) *Event*, (2) *Game Situation*, and (3) *Equipment*. Each subscale contains a list of mutually exclusive items in which the rater could choose only one item. Its content was based on variables of interest generated by initial exploratory video analysis, the research team's extensive research and experience related to hockey and concussions, consultation with players and coaches external to the research team, and review of the literature.

The *Event* section includes most of the key information about the physical context in which the player was injured, including mechanism of injury. This section is further divided as follows: (a) **Scenario** identifies the context that precipitated the eventual injury. For example, did the scenario involve another player (e.g., With Teammate or With Opponent) or an unprecipitated trip or fall

(Other); (b) **Initial Contact With** identifies the body part (e.g., Head, Elbow, Shoulder, Gloves/Fist) or object (e.g., Stick or Puck) that first contacted the injured player in the Scenario; (c) **Region** identifies the anatomical region of the player receiving the contact (e.g., Head/Face or Torso); (d) **Location** refers to the anatomical aspect of the Region struck. For example, if a player is struck directly in the mouth by an opponent's stick, then it would be classified as anterior; (e) **Acceleration of Head** identifies the biomechanical plane(s) of the player's head motion that might have occurred during the Event; (f) **Secondary Contact**; and (g) **Tertiary Contact**. Both of these latter two categories apply only to physical contacts after the initial contact has been evaluated. Specifically, these categories identify if any additional forces have been applied to the player's head after the initial contact has occurred (e.g., ice surface or boards).

The *Game Situation* section describes the physical area in the rink where the player was injured and captures the basic elements of the play: (a) **Zone** identifies the area of the ice rink consisting of offensive, defensive, and neutral areas; (b) **Location** identifies a more precise location within the zone (e.g., open ice, behind the net, corner, etc.); (c) **Situation** describes the hockey specific actions during which the Event occurred (e.g., breakout, on the rush, forecheck, etc.); (d) **Puck Possession** identifies if the injured player had control of the puck while attempting a hockey related skill (e.g., skating); (e) **Period** is the defined timeframe of play in the NHL, each period consisting of 20 minutes of stop-time play; and (f) **Penalty** identifies a rule violation, enforced by on-ice officials.

The third section, *Equipment*, describes the facial protective equipment used by the player at the time of injury. Specifically, the HUC captures whether the injured player was wearing (a) **Mouthguard**, and/ or (b) **Visor**.

Finally, the HUC includes a schematic of the ice surface, with space available for viewer commentary (See Figure 1).

2.2.2 Statistical Analysis

Agreement emphasizes the interchangeability, or the absolute consensus, between judges and is typically indexed via some estimate of between-rater discrepancy. Total percent agreements (TPA) is a simple method that uses the ratio of the number of ratings for which both the raters agree to the total number of ratings. Kappa coefficients use a similar approach, with the correction factor that allows for agreement occurring by chance. That is, Kappa coefficients are calculated by considering the observed percentage (proportion of where the raters agree) and the expected proportion (proportion of agreements that are expected to occur by chance as a result of the rater scoring in a random manner).⁹⁸

In Study 1, four raters completed the HUC for a sample of 25 concussion events drawn randomly from the 2006-2007 NHL season. TPA and Kappa coefficients were calculated for the expert and naïve raters separately. For Study 2, TPA and Kappa coefficients were calculated to determine the strength of inter-rater agreement between the two expert raters.

2.3 Results

2.3.1 Study 1

Table 1 provides a summary of the inter-rater reliabilities for both the naïve and expert raters. For the naïve raters, 12 of the 15 items had a total percent agreement (TPA) value of 0.70 or higher. Kappa values were lower, ranging between 0.23-0.95. However, for the expert raters, 14 of the 15 factors scored a TPA value of 0.80 or higher. Again, similar to the naïve raters, Kappa values were generally lower, with values ranging between 0.31-0.95. Expert viewers had a greater number of factors with Kappa values of >0.50 than the naïve viewers.

Table 1. Summary of inter-rater reliabilities for naïve and expert raters (n=25)

	Expert Raters		Naïve Raters	
	TPA	Kappa	TPA	Kappa
Event				
Scenario	1.00	1.00	0.96	0.471
Initial Contact With	0.96	0.876	0.84	0.812
Region	0.88	0.613	0.88	0.747
Body Location	0.84	0.672	0.68	0.331
Acceleration of Head	0.56	0.308	0.52	0.353
Secondary Contact	0.80	0.684	0.64	0.560
Tertiary Contact	0.88	0.603	0.72	0.310
Game Situation				
Zone	0.92	0.868	0.96	0.931
Ice Location	0.96	0.945	0.72	0.945
Game Situation	0.88	0.893	0.96	0.889
Puck Possession	0.80	0.604	0.80	0.609
Period	0.88	0.934	0.92	0.912
Penalty	0.88	0.805	0.76	0.468
Equipment				
Mouthguard	0.88	0.579	0.72	0.230
Visor	0.96	0.925	0.96	0.925

Overall, the majority of the agreement values were acceptable; however, Study One highlights some of the challenges in ascertaining specific variables of interest relating to Acceleration of Head, Body location, Mouthguard, Puck

Possession, and Scenario. The quantitative discordance values and qualitative feedback from the raters resulted in refinement of the HUC (v 1.1) prior to Study 2.

Table 2. Heads Up Checklist (HUC) factors

Event	Game Situation	Equipment
Scenario	Zone	Visor
Initial Contact With Region	Ice Location Situation	Mouthguard **
Body Location	Puck Possession	
Acceleration of Head	Period	
Secondary Contact	Score *	
Tertiary Contact	Medical Attention *	
Anticipated Hit *		

* Factors added to HUC v 1.2

** Factor removed in HUC v 1.2

Figure 1. Heads Up Checklist (v 1.2)

HEADS UP CHECKLIST

ID: _____

RATER: _____

EVENT

SCENARIO:	INITIAL CONTACT WITH:	REGION :	LOCATION:
<input type="checkbox"/> With teammate	<input type="checkbox"/> Stick	<input type="checkbox"/> Head/Face	<input type="checkbox"/> Anterior
<input type="checkbox"/> With opponent	<input type="checkbox"/> Head	<input type="checkbox"/> Neck	<input type="checkbox"/> Posterior
<input type="checkbox"/> With official	<input type="checkbox"/> Gloves/Fist	<input type="checkbox"/> Other	<input type="checkbox"/> Lateral
<input type="checkbox"/> Fall or trip	<input type="checkbox"/> N/A	<input type="checkbox"/> Inconclusive	<input type="checkbox"/> Inconclusive
<input type="checkbox"/> Other	<input type="checkbox"/> Puck	<input type="checkbox"/> Below Waist	
<input type="checkbox"/> Inconclusive		<input type="checkbox"/> Inconclusive	

ACCEL. OF HEAD:	SECONDARY CONTACT:	TERTIARY CONTACT:	EQUIPMENT
<input type="checkbox"/> Sagittal or coronal	<input type="checkbox"/> Goal/Net	<input type="checkbox"/> Goal/Net	VISOR:
<input type="checkbox"/> Transverse	<input type="checkbox"/> Skater	<input type="checkbox"/> Skater	<input type="checkbox"/> Yes
<input type="checkbox"/> Multi-plane	<input type="checkbox"/> Boards	<input type="checkbox"/> Boards	<input type="checkbox"/> No
<input type="checkbox"/> Inconclusive	<input type="checkbox"/> Inconclusive	<input type="checkbox"/> Inconclusive	<input type="checkbox"/> Inconclusive

Refers only to contact to head

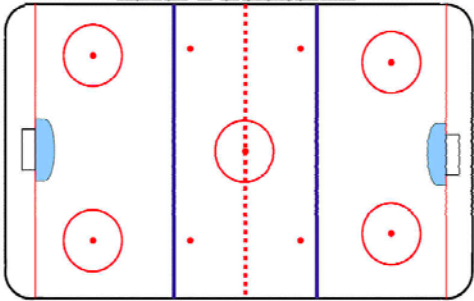
GAME SITUATION

ZONE:	LOCATION:	SITUATION:	PUCK POSSESSION:
<input type="checkbox"/> Offensive	<input type="checkbox"/> 1 = Side Boards	<input type="checkbox"/> Breakout	<input type="checkbox"/> Yes
<input type="checkbox"/> Defensive	<input type="checkbox"/> 2 = Corner	<input type="checkbox"/> Backcheck	<input type="checkbox"/> No
<input type="checkbox"/> Neutral	<input type="checkbox"/> 3 = End Board	<input type="checkbox"/> On the Rush	<input type="checkbox"/> Just Released
<input type="checkbox"/> Inconclusive	<input type="checkbox"/> Behind Net	<input type="checkbox"/> Forecheck	<input type="checkbox"/> Inconclusive
	<input type="checkbox"/> Side of Net	<input type="checkbox"/> Transition	
	<input type="checkbox"/> 4 = Open Ice	<input type="checkbox"/> Other	
	<input type="checkbox"/> Inconclusive	<input type="checkbox"/> Retrieving Puck	
		<input type="checkbox"/> Fight	
		<input type="checkbox"/> Inconclusive	

ANTICIPATED HIT:	ON-ICE MEDICAL ATTENTION:	
<input type="checkbox"/> Yes	<input type="checkbox"/> Yes	
<input type="checkbox"/> No	<input type="checkbox"/> No	
<input type="checkbox"/> Inconclusive	<input type="checkbox"/> Inconclusive	

GAME SHEET	PENALTY:	SCORE:	
PERIOD:	<input type="checkbox"/> Yes - see comments	<input type="checkbox"/> Winning	
<input type="checkbox"/> 1st	<input type="checkbox"/> No	<input type="checkbox"/> Losing	
<input type="checkbox"/> 2nd	<input type="checkbox"/> Inconclusive	<input type="checkbox"/> Winning > 2 goals	
<input type="checkbox"/> 3rd		<input type="checkbox"/> Losing > 2 goals	
<input type="checkbox"/> Overtime		<input type="checkbox"/> Tie Game	
<input type="checkbox"/> Inconclusive		<input type="checkbox"/> Inconclusive	

Mark an "X" of event on rink



COMMENTS:

PLEASE ENSURE ALL FIELDS ARE COMPLETED

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2.3.2 Study 2

In HUC v 1.2, the mouthguard factor was eliminated due to difficulty with identifying the presence or absence of a mouthguard in a reliable manner. In addition to revising some operational definitions and adding examples of common responses of existing factors, three additional factors were added. Score, Anticipated Hit, and On-ice Medical Attention were incorporated into the HUC v 1.2, resulting in 17 variables of interest (See Figure 1 and Table 2). Table 3 presents the reliability findings for each item on the HUC (v 1.2), including TPA and Kappa values. All of the items had a TPA value of greater than 0.80 for the expert raters. In addition, all items had Kappa values of >0.68 . Acceleration of Head (Kappa = 0.734, 95% CI: 0.652, 0.816), Region (Kappa = 0.746, 95% CI: 0.640, 0.852), and Anticipated Hit (Kappa = 0.687, 95% CI: 0.589, 0.786) had the lowest Kappa values. An overall reliability value was calculated based on the 14 subjective components of the HUC. Penalty, Period, and Score were not included in the overall calculation as this information was obtainable from additional sources. The overall reliability of the HUC based on TPA and Kappa values was 0.906 (SD = 0.06) and 0.846 (SD = 0.10), respectively.

Table 3. Summary of inter-rater reliabilities for expert raters (n=174)

	TPA (95% CI)	Kappa (95% CI)		TPA (95% CI)	Kappa (95% CI)
Event			Game Situation		
Scenario	0.994 (0.98, 1.00)	0.974 (0.92, 1.00)	Zone	0.977 (0.96, 0.99)	0.972 (0.94, 1.00)
Initial Contact With	0.855 (0.80, 0.91)	0.794 (0.72, 0.87)	Ice Location	0.930 (0.89, 0.97)	0.896 (0.84, 0.95)
Region	0.895 (0.85, 0.94)	0.746 (0.64, 0.85)	Game Situation	0.901 (0.86, 0.95)	0.888 (0.84, 0.94)
Body Location	0.860 (0.81, 0.91)	0.764 (0.68, 0.85)	Puck Possession	0.878 (0.83, 0.93)	0.822 (0.75, 0.89)
Acceleration of Head	0.808 (0.75, 0.87)	0.734 (0.65, 0.82)	Period	N/A	N/A
Secondary Contact	0.849 (0.79, 0.90)	0.805 (0.74, 0.87)	Penalty	N/A	N/A
Tertiary Contact	0.948 (0.92, 0.98)	0.834 (0.73, 0.94)			
Equipment			Other		
Visor	0.977 (0.95, 0.99)	0.956 (0.91, 0.99)	Score	N/A	N/A
			Anticipated Hit	0.820 (0.76, 0.88)	0.687 (0.59, 0.79)
			Medical Attention	0.983 (0.96, 1.00)	0.971 (0.94, 1.00)

2.4 Discussion

The purpose of these two studies was to develop operational definitions, valid constructs, and a reliable way to encode and analyze digital video records of concussive events in NHL hockey. The main outcome of the present paper was the development of HUC (v 1.2) as a reliable tool for thorough description and documentation of the situational contexts and mechanisms of concussions in hockey by video analysis. Although hockey is a complex and fast-paced game where it is often difficult to identify and classify various playing actions, the inter-rater agreement for many of the variables developed in the HUC was quite high, indicating that the process of coding video information can be both valid and reliable.

In the first study, two naïve and two expert raters independently rated 25 events diagnosed as concussions from the 2006-2007 NHL season. Total percent agreements for the items proved to be reasonably high for the naïve and expert raters, with the majority of categories greater than 0.70. Portney and Watkins⁹⁹ previously categorized Kappa coefficients above 0.8 were interpreted as excellent, 0.6-0.8 as substantial, 0.4-0.6 as moderate, and below 0.4 as poor. Therefore, the Kappa coefficients from the first study indicate that the inter-rater reliability of the majority of the HUC items was substantial to excellent. Although the overall inter-rater reliability of the HUC was acceptable, the results from Study 1 identified some deficiencies within this tool.

The items with lower agreement levels in version 1.1 were Acceleration of Head, Body Location, Mouthguard use, Puck Possession, and Scenario. The lower inter-rater

reliabilities for these categories were likely a reflection of the raters' inability to clearly differentiate or identify the appropriate coding response. For example, in the development phase of the HUC, we included the mouthguard use item because we expected that the higher resolution and the ability to zoom in that the current digital technology provides would afford viewers a greater level of visual detail. However, the ability to correctly identify the presence or absence of a mouthguard in a reliable manner was unattainable even with the current technologies. Given the nuances of correctly identifying a mouthguard (e.g., on the ice, in the player's glove, removed by first responder, lack of refined detail in video, etc.), we decided to eliminate this item in future iterations of the HUC. There has been much debate regarding the efficacy of mouthguards in the prevention of concussions^{100, 101} and it is necessary for researchers to explore this issue in greater depth. It would be useful for a future video analysis study to have access to corroborating medical information confirming presence or absence of a mouthguard.

Two other categories with lower inter-rater reliability values – Puck Possession and Acceleration of Head – were of greater concern. We believe the discordance for these two categories was due to the lack of clarity in the operational definitions that accompanied the initial HUC. Prior to Study Two, operational definitions of puck possession and acceleration of head items were revised. Clear descriptions with examples of each item were added to the most recent version of the HUC to illustrate typical behaviour.

One of the main objectives of including both naïve and expert raters in the first study was to ensure the HUC and corresponding user manual were developed so that

individuals with limited hockey knowledge could be trained to reliably code for the majority of circumstances and mechanisms leading to concussion. Overall, the reliability findings support the utility of the HUC as a sufficient tool to code events reliably via video analysis among independent raters with different levels of hockey knowledge.

Along with removing Mouthguard use and revisions to a few of the variables and operational definitions, we added three additional factors prior to the second study. Score, Anticipated Hit, and On-ice Medical Attention were incorporated into the HUC, resulting in 17 variables of interest. Anticipated Contact and On-ice Medical Attention were included to provide relevant information associated with injury severity and potential patterns of injury mechanisms. For instance, are the collisions that result in an injured player receiving medical attention on the ice – often spectacular to some viewers – associated with any particular injury mechanism? The Score variable was added to consider the context of the game when concussions potentially happen more often. For example, are these injuries more likely to occur when the score is close or when the margin of goals is large between the two teams?

The most recent version of the HUC (v 1.2), which includes 17 variables of interest, was used by the two expert raters in the second study. The results of the second study indicated that all of the items had a TPA of greater than 0.80, a cut-off commonly regarded as necessary for agreement.^{102, 103} In addition, all items had Kappa coefficients of greater than 0.68; therefore, all of the categories are considered to have substantial to perfect inter-rater agreement estimates.^{99, 104} Collectively, the findings support the HUC as a reliable coding tool in describing the situational contexts and

mechanisms of concussions in hockey by video analysis. With this reliable methodology in place, the next step was to accurately describe the characteristics of concussions at the NHL level.

2.4.1 Limitations

Despite the promising utility of the HUC, some methodological shortcomings warrant discussion. First, although the HUC sufficiently describes the situational context and mechanisms of concussion, it is important to keep in mind that this method does not attempt to determine the precise point in time when the injury occurred. This is consistent with previous video analysis studies where it has been recognized that the exact moment of injury cannot be determined with this method.¹⁰⁵ Second, the HUC has been developed to evaluate documented concussions in hockey; but, presumably some concussions were not reported and thus, could not be analyzed. The degree to which the under-representation of the incidence of injury affects our results is unknown. Also, even though the NHL is the ideal study ground for a project of this nature given the amount of high quality video coverage available, some of the digital video was of less than optimal quality and was captured from a limited number of views. Overall, the proportion of our digital video images that had poor quality was small, but this may have contributed to some discordance between raters. With that in mind, the video analysis approach may not be as effective in other leagues from which the quantity and quality of video imaging records may not be as high.

Common sense indicates that the video analysis approach is an appropriate method to describe playing situations and athlete-opponent movements, but insufficient

to provide detailed biomechanical information. Despite the potential limitations in the assessment of biomechanical factors, we wanted to attempt to capture and document the movement of the head related to mechanism of injury. Specifically, the Acceleration of Head item was included to qualitatively describe rotation of the head. It was initially important for the HUC to document such information, as the literature suggests that greater severity of brain injury is associated with axonal shearing that accompanies head rotation.^{106, 107} However, the Acceleration of Head item scored fairly low in the first study so it was revised prior to the second study. This item had the lowest inter-rater agreement coefficient in Study 2; admittedly, it did not perform as well as expected. Thus, a detailed biomechanical component may be beyond the scope of ability for the HUC.

2.4.2 Conclusion

Collectively, Study 1 and Study 2 showed high to very high inter-rater agreement of items on the HUC. The HUC is a reliable objective recording tool that accounts for the situational contexts of injury (playing situation, player and opponent behaviour), and a description of its mechanism. With such a framework established for video analysis of injury, it is reasonable to assume that if high quality digital video images are available, the HUC may be applied to various levels of play (e.g., university or collegiate) or even modified to address a particular injury (e.g., ACL injury). At present, the use of the HUC allows us to capture the information necessary for a better understanding of concussions in hockey, and may allow us to generate hypotheses or recommendations to prevent concussions at the NHL level.

3 Chapter 3

Systematic Analysis of National Hockey League Concussions, Part I: the 4 Ws of concussion

Please note: for purposes of this thesis the 4 Ws refer to:

1. WHO gets a concussion?
2. WHEN do concussions happen?
3. WHERE on the ice do concussions occur?
4. Under WHAT circumstances do concussions happen?

3.1 Introduction

Hockey is a popular sport, and at its highest levels, it is a complex contact game involving the combination of physical strength, speed, agility, diverse physiological demands, and technical mastery. In addition to these necessary attributes, players must execute the sport within an enclosed area containing hard surfaces and obstacles such as surrounding boards and glass, ice, goal nets, officials, and perhaps most importantly – their opponents. Given all of these interacting variables, the risk of injury is significant. Of particular concern among the medical and public communities is one of the most common injuries in hockey, namely concussion.^{39-41, 108-111}

The National Hockey League (NHL) is regarded as the premier league where many of the best players in the world compete against each other. As part of the league's strategy to monitor and manage health or related issues, the league and the NHL Players' Association (NHLPA) implemented the NHL/NHLPA Concussion Program in 1997. This hybrid clinical care/research effort was the first of its kind in professional sports, and has focused on understanding the effects of concussions and validating objective measures for its management.

Understanding the natural recovery that happens following concussion is necessary because it guides appropriate and prudent management of the injury. The sequelae of concussion are now well documented.^{52, 54, 55, 59, 87-91, 112, 113} However, very little is known regarding the mechanisms associated with concussion in hockey. Certain risk factors have been reported, such as increased susceptibility for players in the forward position,^{40, 41} but a thorough description of intrinsic and extrinsic risk factors for concussion has not been completed at the NHL level. Sport-specific knowledge of the mechanisms of an injury and the associated risk factors leading to that injury will help inform future prevention strategies.

Although knowledge of how injuries occur is critical, it is often difficult to determine injury mechanisms on the basis of information from injured players or observation by other people. On the other hand, analysis of injury mechanisms captured on video appears to be a promising approach to objectively identify and understand the injury mechanisms.^{105, 114-116} Specific to hockey, a pilot video analysis study under the auspices of the NHL was undertaken; however, their effort was

dependent on VHS tapes, which because of technological limitations, proved to be too time consuming and ineffective for researchers purposes.⁸⁵

More recently, the quantity and quality of video imaging records of NHL games made it a viable study ground for a video analysis project. Consequently, a project was initiated to examine the events leading to, and the mechanism of, concussion in NHL players. This paper summarizes several important aspects of this work, specifically focusing on the description of players' characteristics, antecedent events, and contextual variables associated with events leading to concussion at the NHL level.

3.2 Methods

During regular season league play between September 1, 2006 – December 31, 2009, digital video images of events that resulted in concussion were analyzed and cross-referenced with league injury reports from the teams' medical staff. Demographic information (i.e., height, weight, and position) of players with concussion was provided by the NHL. Team physicians determined the diagnosis of concussion. Researchers obtained permission and cooperation from the NHL and NHLPA to review all digital video images from the seasons between 2006-2010. The research ethics review board of the University of Toronto approved the study.

3.2.1 Heads Up Checklist

The Heads Up Checklist (HUC) provides a standardized framework to allow a person viewing digital video images a valid way of coding and accounting for the

majority of circumstances and mechanisms leading to concussion. Initial development of the HUC occurred iteratively, in collaboration with other hockey experts in a consensus manner, including Concussion Working Group Members. The HUC consists of 17 groups of factors, categorized within three main domains: (1) Physical Event, (2) Equipment, and (3) Game Situation. In addition to these factors, the HUC includes a schematic of the ice surface and space available for qualitative viewer commentary (See Figure 1 in Chapter 2).

Inter-rater reliability for the coding of the HUC items was tested among four raters (see Chapter 2). This reliability assessment was carried out together in the first phase of the larger study. The purpose of the preliminary study was two-fold: first, to ensure the HUC was able to reliably capture and code relevant information related to the events leading to concussion; second, to indicate changes needed to improve the reliability of ratings in order to produce the current version of the HUC.

Based on percent agreement and Kappa values, the current version of the HUC appears to have “fair” to almost perfect reliability estimates. All of the items were reported to have percent agreements (i.e., total number of concordant observations divided by total number of paired observations) values of > 0.70 . In addition, all items had Kappa (i.e., observed agreement minus expected agreement divided by one minus expected agreement) values of > 0.65 (see Chapter 1).

3.2.2 Procedure

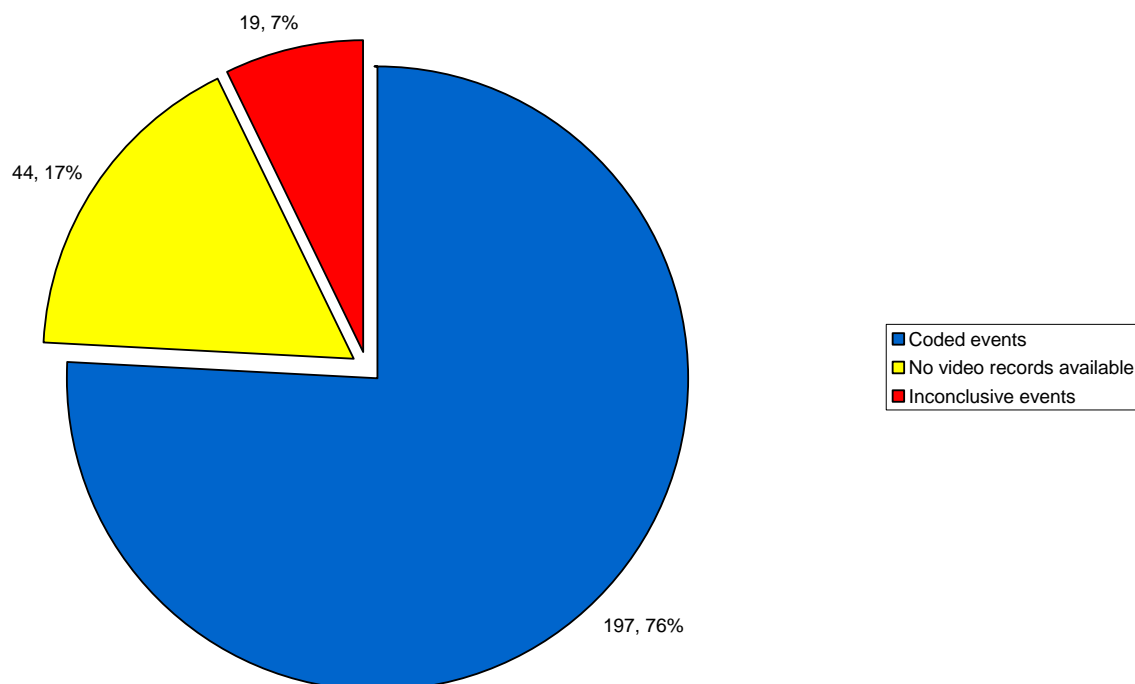
Two raters viewed the digital records of events leading to concussion independently. Raters viewed each event using Quicktime Player Pro Version 7.6.6 software resident on an Apple MacBook Pro 4.1 (operating software Mac OS X Version 10.5.8).⁹⁶ Each category of the HUC was completed for each distinct concussion event. Raters were allowed to view the event as many times as required, in any playback speed deemed necessary to complete all categories on the HUC. If there was initial disagreement, raters viewed and discussed video records of events to determine consensus. For reporting purposes, in cases where consensus was reached, a single value is reported (e.g., 44% of events analyzed occurred in the defensive zone). In cases where consensus was not reached, individual results from each rater or ranges will be reported (e.g., Rater 1 $n = x$; Rater 2 $n = y$ or $n = x - y$).

Data were entered and coded in Statistical Analysis Software (SAS), version 9.2. The χ^2 test was used to examine differences with 95% confidence intervals to measure the magnitude and direction of these differences, and p values set at < 0.05 .

3.3 Results

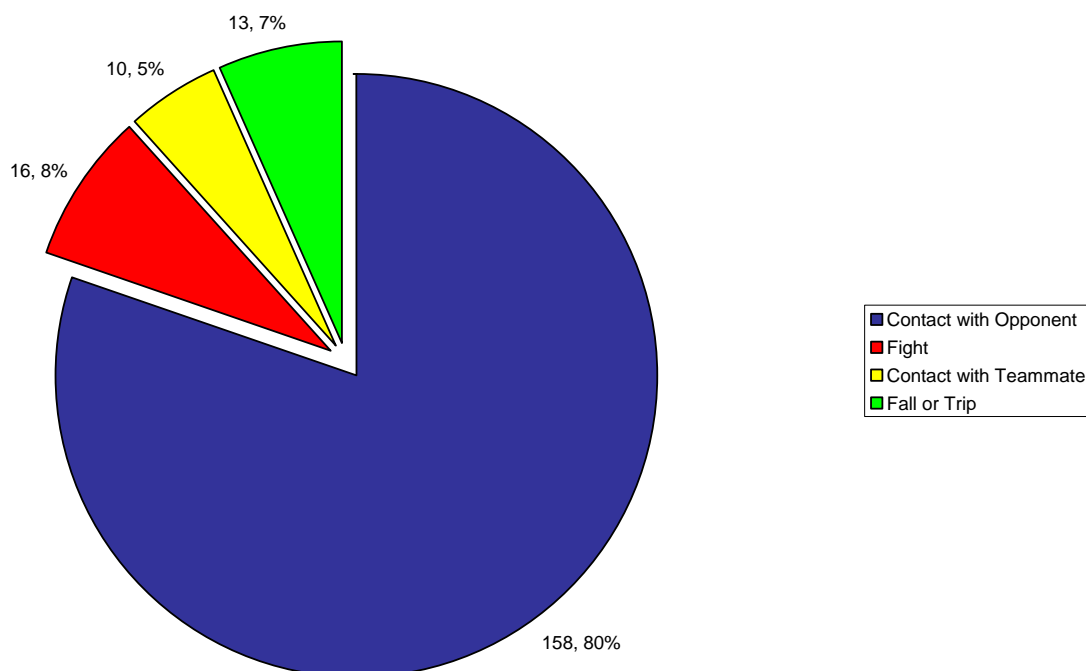
A total of 260 regular season concussions were reported to have occurred during the data collection period; that is, 6.05 injuries per 100 games. Video records for 216 events that resulted in concussion were received from the NHL. Of these, 197 were identified by raters and coded for the present study. Nineteen events were deemed inconclusive by the raters and were therefore not coded by the raters. Figure 2 is the breakdown of concussions during the study period.

Figure 2. Regular Season Concussions in the NHL (N = 260)



See Figure 3 for breakdown of coded events. The most common situation leading to concussion was a result of contact with an opponent [88%, $n = 174 / 197$]. Of these events with an opponent, 16 (8%, $n = 16 / 197$) were classified as a fight. The remaining events were a result of a fall or trip (7%, $n = 13 / 197$) and 10 (5%, $n = 10 / 197$) involved contact with a teammate.

Figure 3. Breakdown of coded events (n = 197)



3.3.1 Who gets a concussion?

Age and anthropometric characteristics: The average age of the players in the injured sample was 28.0 years old (n = 196; *SD* = 4.73, Range 19-40). On average, injured players were 73.13 inches tall and weighed 204.57 lbs (*SD* = 14.83, Range 165-257). For the events that involved direct contact with another player, the player delivering the contact leading to concussion was classified as the “hitter”. The average height (inches) and weight (lbs) of the hitter were 73.59 (n = 174; *SD* = 2.20, range = 68-81) and 212.38 (n = 174; *SD* = 17.05, range = 178 – 257), respectively. In addition to group

averages, case-by-case analyses were conducted, which examined the difference for height and weight between the injured players and hitters. These analyses identified that in 52% of the events, the hitter was taller than the injured player; in 65% of events, the hitter was heavier than the injured player.

Visor usage: In the events analyzed from 2006-2010, 49% (n = 98) of the players were wearing a visor at the time of injury. Over the data collection period, the percentage of players wearing a visor at the time of injury increased from 38% in 2006-2007 to 59% in 2008-2009 (See Table 4).

Table 4. Players wearing a visor at the time of injury [Percentage (number)]

	2006	2007	2008	2009
Yes	38% (19)	48% (30)	59% (29)	53% (19)
No	54% (26)	47% (30)	35% (17)	47% (17)
Inconclusive	8% (5)	5% (2)	6% (3)	0%
Totals (n=197)	50	62	49	36

Player position: Sixty five percent (n = 129 / 197) of the documented concussions were incurred by forwards, 32% (n = 63 / 197) defensemen, and 3% (n = 5 / 197) goalies. The expected distribution of concussions by position based on their proportional representation on the ice would be 50% forwards, 33% Defensemen, and 17% goalies. Four concussions were reported for goalies during the study period; therefore, goalies accounted for fewer concussions than expected when considering on-ice representation. The observed number of concussions for forwards in the present study

was significantly higher than expected compared to on-ice representation ($P = 0.04$, 95% CI: 60 to 73).

When specifically looking at the events restricted to those involving direct contact with an opponent, and not classified as a "fight", 158 events were retained. Of these 158 events, the hitter was a forward in 65% of the cases. Overall, it appears that the forward position is an important factor, as the findings identify the relative proportion of injuries are higher than expected among forwards for both the players being injured and the players delivering the contact leading to concussion.

3.3.2 **When** do concussions happen?

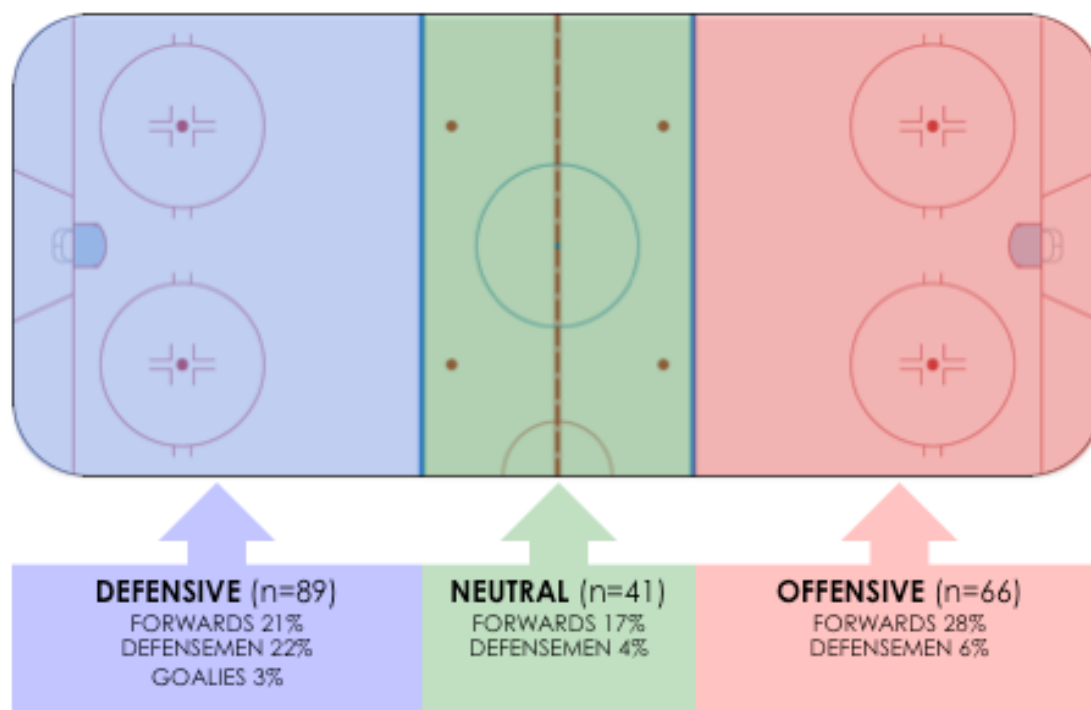
The majority of the concussions occurred in the first period of play, accounting for close to half the events captured on video (47.3%; $n = 86$). There was a relatively equal distribution of concussions occurring between the second and third periods, accounting for 27.3% ($n = 50$) and 25.1% ($n = 46$), respectively [$\chi^2(9, N = 183) = 8.64, p = 0.047$]. Overtime injuries were attributed to the final period. Of note, we were unable to determine the period the player was injured in 14 events.

3.3.3 Where on the ice and under what circumstances do concussions happen on the ice?

Where:

Zone: In total, 89 events (45%, $n = 87 / 197$) occurred when the injured player was in his defensive zone, whereas 66 (33%, $n = 66 / 197$) events occurred when the injured player was in the offensive zone. There were 41 (21%, $n = 41 / 197$) events in the neutral zone and the remaining event was classified as inconclusive. See Figure 4 for the breakdown of player position by zone.

Figure 4. Breakdown of concussions by player position and zone



* Percentages were calculated on the denominator $n = 197$

** Also, one concussion sustained by a defenseman was inconclusive in terms of on-ice location.

The majority of defensemen were injured in the defensive zone. Particular game situations accounted for the majority of concussions for defensemen, which were characterized as “retrieving the puck” or as “breakouts” (See Table 5). In contrast to defensemen, the distribution of location across specific zones was relatively equal for forwards, with a marginal increase suffering a concussion in the offensive zone. Particular game situations were associated with concussion among forwards as well. Situations classified as “on the rush”, "forechecking", and "breaking out" were the actions that accounted for the greatest percentage (See Table 5).

Table 5. Game situations by position. [Percentage (number)]

	Forwards (N=129)	Defensemen (N=63)
Breakout	17% (20)	17% (11)
Retrieving Puck (Defensive Zone)	11% (14)	30% (19)
Forecheck	19% (23)	3% (2)
On the Rush	30% (36)	6% (4)
Fight	8% (10)	10% (6)
Other	20% (26)	33% (21)
Total	100% (129)	100% (63)

Location: The ice surface can be divided into two general areas: the perimeter and the open ice. The perimeter is comprised of the side boards, corners, end boards, and side of net. Side boards refer to the boards and glass and three feet of the ice surface from the boards towards the middle of the rink, spanning all three zones. The corners refer to the rounded portion of the boards and glass connecting the side boards and end boards, including three feet toward the middle of the rink. The open ice is the interior portion of the ice not accounted for in the operational terms described in perimeter. Forty-six percent (Rater 1 n = 92 / 197 ; Rater 2 n = 91 / 197) of the events analyzed were classified as open ice events. Fifty-three percent (Rater 1 n = 106 / 197; Rater 2 n = 105 / 197) of the events were classified as perimeter; of these, 15% (n = 30 / 197) occurred in the corners, 24% (Rater 1 n = 47 / 197; Rater 2 n = 49 / 197) at the side boards, and 13% (Rater 1 n = 26 / 197; Rater 2 n = 27 / 197) at the end boards and the side of net. Of the 197 events, approximately 35% (Rater 1 n = 68 / 197 ; n = 71 / 197) involved the injured players' head contacting the boards or glass (see Table 6 for percentage of events that involved head contact with boards or glass).

Table 6. Events that involved head contact with boards or glass.

Location	Percentage (number)
Side Boards	15% (29-30)
Corner	12% (23-24)
End Boards	8-9% (16-17)
Total	35-36% (68-71)

* Percentages were calculated on the denominator n =197

3.4 Discussion

This paper summarizes the descriptive characteristics of players involved in events leading to concussion as well as a breakdown of the antecedent events and contextual variables associated with concussion at the NHL level. In a sport where body contact is regarded a skill, not surprisingly, body contact was often a component of the chain of events leading to concussion. In the events analyzed spanning over three NHL seasons, over 90% of concussions were a result of player-to-player collisions. Previous research at the collegiate and high school levels reported that player-to-player collisions accounted for 45-60% of concussions.^{41, 111} However, that research differentiated between contact with the ice from the boards/glass and direct player-to-player contact, contributing to the lower reported values. For the purpose of the present paper, we did not suggest causation of head injury (or an exact point of injury), as an injury is often a chain of events leading to the outcome (e.g., a player can be struck in the head by another player, then hit the boards or glass, and finally strike the ice). Interestingly, the act of fighting resulting in concussion accounted for only one tenth of the total number of concussions captured on video. The act of fighting is penalized but tolerated in NHL hockey, and is often suggested as a major cause of concussions in hockey, yet this was not the case in our study. The present findings support the work of Goodman et al.,⁴⁰ in which fights accounted for far fewer concussions than expected.

To our knowledge, these data represent the first comparison of anthropometric measures (weight and height) between players with concussion and players delivering the contact leading to concussion in hockey. Our results suggest that players initiating

the contact were often taller and consistently heavier than the players sustaining concussion. We can only speculate about the reason for these differences, but it may be related to increased player size and strength training for specific roles or predisposition for specific behaviour associated with taller and heavier players. The biomechanical analysis of concussion is complex and beyond the scope of this paper. Nonetheless, it is a given principle of physics that heavier players travelling faster have more momentum and kinetic energy and smaller players accelerate more when colliding with larger players. The current results add weight to the call for manufacturers and researchers to improve the protective qualities of equipment to mitigate the energy of collisions.

Unequivocally, the use of full or partial facial protection significantly reduces a player's risk of severe facial injuries.^{8, 117-120} According to data obtained for the health management committee of the NHL, the percentage of players wearing a visor have increased from 34% in the 2003 season to 56% in 2008.¹²¹ The percentages of players' wearing a visor at the time of injury in present study appear similar to the proportion of players wearing visors across the league. Consequently, despite the overall increase in visor use, the present descriptive results indicate that there is no difference in the occurrence of concussions in players who wear helmets with a visor and those without a visor. We acknowledge that there is particular interest in research examining the use of facial protection and its roles in the prevention of concussion; a future paper will examine visor use and concussion more closely.

In an attempt to identify specific locations on the ice where the majority of concussions occur, our results indicate a relatively even distribution of perimeter and

open ice events leading to concussion. It should be noted that 35% of the events involved direct head contact with boards or glass. These findings are slightly higher than numbers previously reported in hockey.⁴¹ Since 1 in 3 concussions involved direct head contact with boards or glass, evaluation and/or changes in material or installation methods need to be investigated. There are various rink designs (i.e., installation of boards and corresponding rigidity) and several types of glass types installed in ice rinks; however, a comparison of these various designs was not available for this project. Nonetheless, future research examining specific infrastructure standards and designs to dissipate or absorb the energy of these contacts would be a worthwhile avenue to pursue and could potentially lead to the reduction of concussions.

Close to half of the concussions occurred in the first period. We suspect the high number of concussions that occurred in the first period is due to a number of factors. The first period is a time when the players are full of energy and adrenaline. There may also be a team strategy to initiate body contact in the early stages of the game (i.e., “set the tone”, “establish a forecheck”, etc.). Correspondingly, contacts occur more frequently in this period compared to other periods. The present findings are contrary to the general trend of injuries in hockey, which reported that the first period accounted for approximately 25% of total injuries.⁴¹ In addition, the present findings refute a common myth that concussions in hockey often occur when the players are fatigued, or at points later in the game as acts of violence when the “game is out of hand”.

Our results indicate that forwards are at the greatest risk for concussion. A possible reason for this finding may be that forwards spend a greater amount of time with the puck and are often moving across the ice at full speed, thus increasing their risk

for incidents leading to concussion. Of greater importance was player position by zone, which identified specific risks for forwards and defensemen. For example, defensemen sustained 31% of concussions; however, when considering which zone the event occurred, 21% occurred in the defensive zone, and only 4% and 6% in the neutral and offensive zones, respectively. More specifically, defensemen appear to be at the greatest risk when retrieving the puck or behind the net. On the other hand, forwards were at the greatest risk when they were “on the rush”.

Overall, these findings identify specific situations in which a player appears to be at risk for concussion. Related to this issue is considering how the NHL game has evolved in terms of new rules or enforcement patterns. Following the 2004-05 work stoppage, the NHL instituted a "no redline" rule and enforcement of rules to prevent "obstruction" in an attempt to "open up" the game. We can only speculate the degree to which these issues have influenced our findings. In the context of these rules, specific sport related actions appear to be inherently risky (e.g., retrieving the puck or on the rush). We cannot empirically test this point given data collection began in 2006-07; nevertheless, this issue warrants further investigation.

3.4.1 Limitations

There are limitations associated with a project of this nature. The diagnosis of sports-related concussion is a challenge facing sports medicine professionals. Our dataset was restricted to diagnosed concussions only; we recognize the actual number of concussions may be higher as there is a tendency of athletes to under-report or mask symptoms.¹²² Although the NHL has one of the most comprehensive concussion

programs in all of sports, not all concussions were evaluated via video analysis. Nevertheless, we were able to analyze over 75% of concussions during the data collection period; therefore, we believe our results are representative of the typical events leading to concussion at the NHL level. Finally, we analyzed documented concussions in one particular league with its own set of rules and standards (e.g., face shields are optional, fighting is tolerated, touch icing, etc); the extent to which findings can be generalized to other leagues with different sets of rules and regulations is uncertain. Nonetheless, there are a number of important issues highlighted in this paper that are applicable to the hockey community at large.

3.4.2 Conclusion

A sport that involves frequent and forceful collisions between players is inherently risky. The objective of this research was to identify potential factors associated with concussions at the NHL level, which may in turn inform future preventive strategies. We were able to identify several specific risk factors for concussion in NHL players, including: body size, specific locations on the ice, and particular situations based on a player's position. Based on this evidence, players and coaches need to be aware of these specific characteristics and situations associated with concussion. The next step is to develop and implement preventive measures and strategies to minimize these risks. For example, educational videos have been shown to be successful in the prevention of other sport injuries (e.g., ACL injuries in skiing and ankle sprains in volleyball).^{83, 123} Consideration of educational videos could be done on a one-on-one basis with players and coaches or used as a tool to teach avoidance

strategies associated with particular situations. Overall, raising awareness through education is likely the most effective approach in decreasing the number of these potentially debilitating injuries.

4 Chapter 4

Systematic Analysis of National Hockey League Concussions, Part II: How

4.1 Introduction

The modern game of hockey has evolved into its current state largely due to significant advances in equipment technology, incorporation of year round physical conditioning, and refined coaching strategies. Present day games in the National Hockey League (NHL) are played by larger, faster, and more skillful players than in previous decades.^{124, 125} However, the fundamental tenets of the game have remained stable over time, with even strength play consisting of five-on-five play executed within an enclosed area (200' x 85'). With more than 50,000 body contacts occurring over the course of the year, body checking remains an integral component and a valued skill.¹²⁶ Given the characteristics of the game, combined with the physical attributes of today's professional player, hockey carries an inherent risk of injury.

In the past decade considerable academic and public attention has focused on the issue of cerebral concussions ("concussion") in hockey, as it is one of the most common injuries across all levels of play and age groups.^{15, 32, 39-44} Concussion is a syndrome thought to represent a type of traumatic brain injury at the less severe end of

brain injury continuum. A concussion occurs when an athlete suffers a traumatically-induced alteration of mental state that may or may not involve a loss of consciousness and/or a period of amnesia.⁴⁸ The most frequent symptoms following a concussion include physical and cognitive complaints such as headache, dizziness, fatigue, sleep disturbance, nausea, and cognitive processing difficulties.^{52, 54, 55, 57-63}

Although concussion is generally regarded as a “mild” form of brain injury, its effects can be debilitating nonetheless. Fortunately, the literature indicates that for the majority of athletes, symptom recovery typically occurs between 10-14 days.^{52, 54, 55, 57-63} Notwithstanding, a percentage of athletes may experience atypical recovery patterns, reporting symptoms and cognitive difficulties for protracted periods. Additionally, there is also growing concern about the potential consequences of repetitive head trauma. Research examining the long-term impact of concussions has not been as extensive to date; however, initial epidemiological studies suggest an association between sport-related concussions and cognitive impairments later in life.^{79, 80} Considering the predictable frequency of concussions in hockey, combined with evidence supporting consequences of concussion in the acute stage and over the long-term, prevention initiatives should be a priority for all involved in the sport.

A necessary first step towards the development of effective prevention initiatives is to understand how concussions happen. Common sense suggests that this is relatively easily determined, that eyewitness accounts of observers, or accounts based on injured players’ memories, provide sufficient information to determine the mechanism of injury. However, eyewitness accounts may be unreliable; acute injuries often occur in a split second and it is therefore difficult to ascertain exact information on the

mechanisms and playing situations leading to injury.¹¹⁵ The use of archived video records affords an objective and more thorough description of injury mechanisms because the information can be viewed repeatedly, thereby allowing the mechanism of injury to be learned rather than assumed. The utility of archived video records to conduct systematic video analyses in various sports has resulted in prevention strategies such as awareness training programs⁸³ and, in other cases, the suggestion for stricter rule enforcement and/or rule changes.^{82, 84}

A large-scale systematic video analysis research project of concussions in the NHL was initiated in 2008. With permission and cooperation of both the league and players' union, the project was an opportunity to investigate both players' and public concerns about concussions in a collaborative research framework, involving a large sample of video records of professional hockey players, in order to make recommendations about potential prevention strategies informed by science. The principal research objectives of the project were to address the "Who, When, Where, What, and How?" of concussions in NHL players. More specifically, the research was intended to answer these questions: 1) What are the characteristics (position, height, weight, etc.) of the athletes who suffer a concussion?; 2) When do concussions happen? and; 3) Where and under what circumstances on the ice do concussions happen? In the first paper of a two-part series, we addressed the four Ws of concussions: *Who, When, Where, and What?* [See Chapter 3]. Building on that article, the purpose of the present (second) paper is to focus on how concussions occur at the NHL level, in order to identify potential pattern(s). Also, two specific contextual issues (i.e., puck possession and penalty) related to injury mechanism will be addressed.

4.2 Methods

We obtained permission and cooperation from the National Hockey League (NHL) and National Hockey League Players' Association (NHLPA) to review all the digital video records and analyze medical records from the NHL Concussion Program database for the regular seasons from 2006-07 through to December 31, 2009. The study was approved by Ethics Review Board of the Office of Research Services at the University of Toronto. Team physicians determined the diagnosis of concussion. Digital video records of events that resulted in diagnosed concussion were analyzed and cross-referenced with league injury reports from the team medical staff.

4.2.1 Heads Up Checklist (HUC)

The HUC was developed to permit a standardized framework to allow a person viewing digital video images a consistent way of coding and accounting for the majority of circumstances and mechanisms leading to concussion. The HUC appears to have fair to high inter-rater reliability estimates. All of the items were reported to have total percent agreement (i.e., total number of concordant observations divided by total number of paired observations) values of > 0.70 . In addition, all items had Kappa (i.e., observed agreement minus expected agreement divided by one minus expected agreement) values of > 0.65 (See Chapter 2). The HUC is organized to capture information into three broad sections: (1) Event, (2) Game Situation, and (3) Equipment. In total, there are 17 specific factors of interest (See Figure 1 in Chapter 2); however, to

understand how concussions happen, the majority of this paper will focus on the discussion pertinent to the Event section.

The *Event* section of the HUC includes most of the key information captured with respect to the context in which the player was injured, including mechanism of injury. This section is further subcategorized as follows: (a) **Scenario** identifies the context that precipitated the eventual injury. For example, did the scenario involve another player (e.g., With Teammate or With Opponent) or an unprecipitated trip or fall; (b) **Initial Contact With** identifies the body part (e.g., Head, Elbow, Shoulder, Gloves/Fist) or object (e.g., Stick or Puck) that first contacted the injured player in the Scenario; (c) **Region** identifies the anatomical region of the player receiving the initial contact (e.g., Head/Face or Torso); (d) **Location** refers to the anatomical aspect of the Region of the player struck. For example, if a player is struck directly in the mouth by an opponent's stick, then it would be classified as "anterior"; (e) **Acceleration of Head** identifies the biomechanical plane(s) of any acceleration that a player's head appears to have undergone during the Event; (f) **Secondary Contact**; and (g) **Tertiary Contact**. Both of these latter two categories apply only to contacts after the initial contact has been evaluated. Specifically, these categories identify if any additional forces have been applied to the player's head after the initial contact has occurred (e.g., ice surface or boards).

4.2.2 Procedure

Two raters independently viewed the digital video records of events leading to concussion. Raters viewed each event using Quicktime Player Pro Version 7.6.6

software resident on an Apple MacBook Pro 4.1 (operating software Mac OS X Version 10.5.8).⁹⁶ Each category of the HUC was completed for each distinct concussion event. Raters were allowed to view the event as many times as required, at any playback speed deemed necessary to complete all categories on the HUC. In cases where there was initial disagreement between raters, video records of events were reviewed to determine consensus. For reporting and discussion purposes, in cases where consensus was reached, a single value is reported. In cases where consensus was not reached, the mean percentage value between the two raters followed by individual results from each rater or ranges will be reported. Data generated from HUC summary sheets were entered and coded in Stastical Analysis Software (SAS), version 9.2.

4.3 Results

A total of 260 diagnosed concussions in 4,299 NHL regular season games from the beginning of 2006-07 season to the end of December 2009 (6.05 / 100 games). Seventy six percent (197 of the 260 concussions) were identified on video and analyzed for the present study (See Figure 2 in Chapter 3).

4.3.1 Scenario

The greatest proportion of events leading to concussion involved contact with an opponent (n = 174 / 197, 88%). See Table 7 for a full breakdown of situations. Of the 174 events involving contact with an opponent, 9% (n = 16 / 197) were classified as a fight. With respect to the 16 events classified as fights, all of them involved direct contact to the head and 75% (n = 12 / 16) involved secondary contact most often by contact to the head by an opponent's fist or by striking the ice surface. The subset of

158 events (174 – 16 [fights] = 158) — the concussions involving an opponent but excluding fights — was used for the majority of the analyses as these events accounted for the majority of concussions.

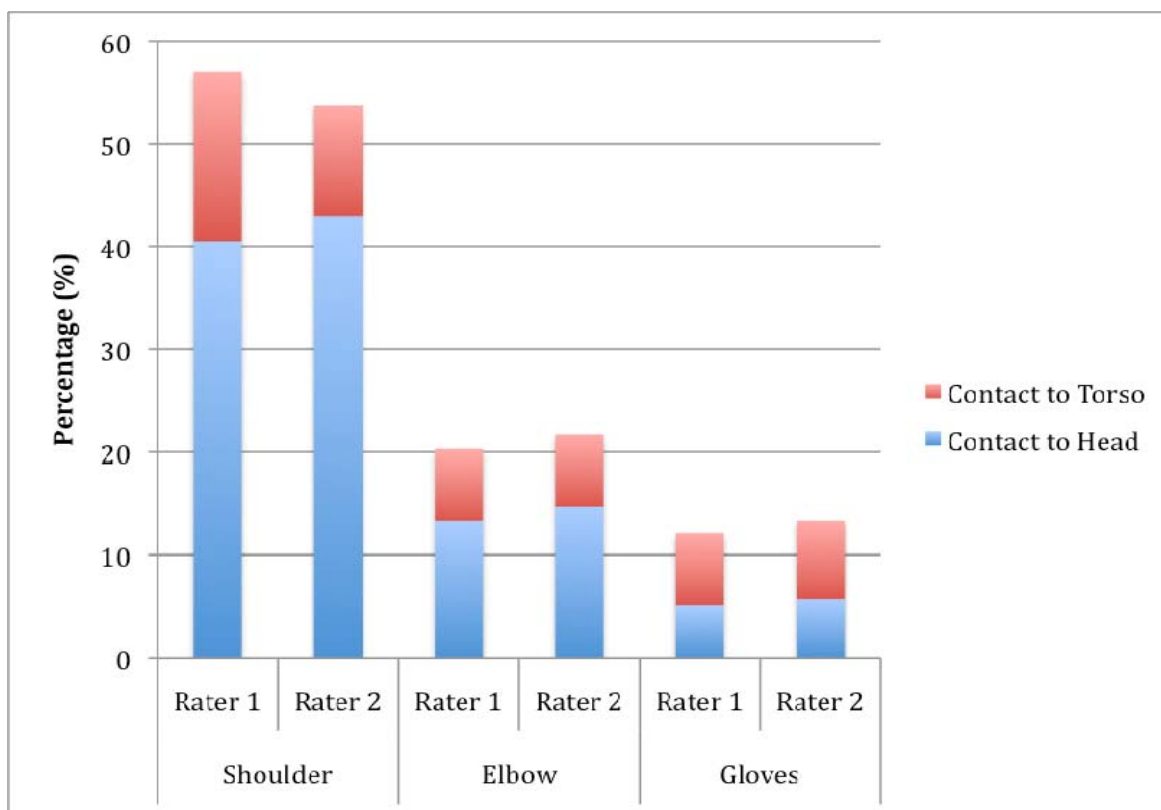
Table 7. Scenario leading to concussion

Scenario	
Contact with Teammate	10
Contact with Opponent	174
Fall / Trip	13
TOTAL	197

4.3.2 Initial Contact With

In order to thoroughly describe the mechanisms of injury leading to concussion, we attempted to understand each event according to its component parts. The first step was to better describe the body part of the hitter that initiates contact with the concussed player. The shoulder was the most common body part involved, followed by the elbow and gloved hands (“gloves”). Therefore, aggregate data identify that the initial contact to any part of the player’s body leading to a concussion was by shoulder (55%), elbow (20%) and gloves (12%), for a total of 87%. See Figure 5 for breakdown by rater.

Figure 5. Initial contact with: first body part of the hitter that initiated contact with the concussed player



* Percentages were calculated on the denominator n =158

4.3.3 Region

The next stage in the analysis was to identify the region or part of the body on the injured player that was initially contacted, which was broadly classified as head, neck, torso, or below the waist. The most common body part contacted first was the player's head (Rater 1 n = 105 / 158, 66%; Rater 2 n = 112 / 158, 71%), while the torso region accounted for approximately 27% (Rater 1 n = 48 / 158; Rater 2 n = 41 / 158). The remaining 11% were classified as one of below the waist, below the neck, or inconclusive.

When the events were filtered to focus on contacts directly to the head in situations involving an opponent and the injured player, as Table 8 identifies, contact was initiated by the shoulder 41% of the time (Rater 1 n = 64 / 158; Rater 2 n = 68 / 158), by the elbow 14% (Rater 1 n = 21 / 158; Rater 2 n = 23 / 158), and by gloves in 5% of cases (Rater 1 n = 8 / 158; Rater 2 n = 9 / 158). In summary, 61% (Rater 1 n = 93; Rater 2 n = 100) of the concussions in the sample of 158 were directly attributed to shoulders, elbows, or gloves to the head of an opponent during the flow of the game.

Table 8. HUC results of initial contact with for each rater

	Head n (%)	Torso n (%)	Totals n (%)
Gloves			
Rater 1	8 (5.1)	11 (7.0)	19 (12.0)
Rater 2	9 (5.7)	12 (7.6)	21 (13.3)
Elbow			
Rater 1	21 (13.3)	11 (7.0)	32 (20.3)
Rater 2	23 (14.7)	11 (7.0)	34 (21.5)
Shoulder			
Rater 1	64 (40.5)	26 (16.5)	90 (56.9)
Rater 2	68 (43.0)	17 (10.8)	85 (53.7)
Other / Inconclusive			
Rater 1			17 (10.7)
Rater 2			18 (11.4)

* Percentages were calculated on the denominator n =158

4.3.4 Body Location and Acceleration of Head

A further refinement was made to identify the specific anatomical aspect (i.e., anterior, posterior, or lateral) of the region of body first contacted. For example, if a player was struck directly in the mouth by an opponent's elbow, then body location would be classified as "Anterior". Table 9 provides a breakdown of events identified as contact to the torso or head, stratified by body location (Anterior, Posterior, or Lateral), from the subset of 158 events involving an opponent. The lateral aspect of the head or torso was the most common mechanism of initial contact (Rater 1 = 93 / 158, 58%; Rater 2 n = 91 / 158, 58%), while initial contact of the anterior and posterior aspects of the head or torso accounted for 20% (Rater 1 n = 32 / 158; Rater 2 n= 33 / 158) and 15% (Rater 1 n = 24 / 158; Rater 2 n = 23 / 158), respectively.

Table 9. Contacts to the head or torso stratified by body location [Percentage (number)]

	Anterior	Posterior	Lateral
Head	18 (28)	3 (3-5)	46-47 (72-75)
Torso	3 (4-5)	11-13 (18-21)	10-13 (16-21)

* Percentages were calculated from the denominator n =158 and ranges reflect discrepancies between raters

* 13% (20 events) were classified as either "other" or "inconclusive"

When the results of anatomical aspect are combined with initial contact, almost half of these events (Rater 1, n = 72 / 158; Rater 2, n = 75 / 158) were classified as direct contact to the lateral aspect of the head. Of importance, a large proportion of these were by shoulder, elbow or gloves (Rater 1, n = 68 / 158, Rater 2, n = 72 / 158). Therefore, we interpret this to mean approximately 35% (Rater 1 n = 68 / 197, 35%, Rater 2 = 72 / 197, 37%) of all concussions during the three and half seasons were

classified as direct impact to the lateral aspect of the head by shoulders, elbows, or gloves.

In addition to the anatomical aspect, raters also documented observable head motion during events that resulted in diagnosed concussion. Most often head acceleration occurred in multiple planes, typically in the sagittal and transverse planes (Rater 1 $n = 62 / 158$; Rater 2 $n = 58 / 158$). There was a relatively even distribution of events classified as sagittal or coronal plane ($n = 40 / 158$) and transverse plane (Rater 1 $n = 42 / 158$; Rater 2 $n = 37 / 158$). Of note, 12% of the events were deemed to have no observable head motion or inconclusive for observable head motion (Rater 1 $n = 18 / 158$; Rater 2 $n = 19 / 158$).

4.3.5 Secondary and Tertiary Contact

Once the mechanism of the initial contact was evaluated, particular attention was paid to documenting additional impacts to the injured player's head. Specifically, secondary contact analysis occurred only when additional contact to the player's head was apparent after the initial contact. For example, if two players contacted each other shoulder-to-shoulder and the injured player fell and struck his head on the ice, *secondary contact* would be identified as "ice". Table 10 provides a breakdown of events by each rater, classified by the context of event and corresponding impacts.

Table 10. Breakdown of secondary and tertiary contacts

Scenario	Events
<i>Fall / trips</i>	13
Boards/glass	7
+ 2 nd contact	2-3
<i>Contact with Opponents</i>	174
Direct impact to head	120-124
+ 2 nd contact	66-67
Boards/ glass	27-28
+ 3 rd contact	16
Body Contact	49-54
+ 2 nd contact	42-47
Boards/ glass	35-36
+ 3 rd contact	7-8
<i>Contact with Teammates</i>	10
Direct impact to head	10
+ 2 nd contact	4-5
Boards / glass	1

** Ranges represent discrepancies between raters

The events that involved direct initial contact to the head (approximately 60%, Rater 1 = 120 / 197 and Rater 2 = 124 / 197) also involved secondary contact to the head (Rater 1 = 66, Rater 2 = 67). Head contact to the boards or glass accounted for the largest proportion of these secondary contacts (Rater 1 = 27 / 66; Rater 2 = 28 / 67).

Furthermore, over 10% ($n = 16$) of these events that involved direct initial contact to the head were not only followed by a secondary contact to the head, but also by a tertiary head contact.

For the events that involved an opponent and initial contact to the body (other than the head), a large proportion (Rater 1 = $47 / 54$, 87%; Rater 2 = $42 / 49 = 86\%$) still involved head contact at some point in the injury sequence. Of these events that involved secondary contact, the head often struck the boards or glass (Rater 1 = $36 / 47$; rater 2 = $35 / 42$). Approximately 17% (Rater 1 = $8 / 47$; Rater 2 = $7 / 42$) of the events that involved secondary contact also involved tertiary contact. Finally, of importance, only less than 5% of the events ($n = 7$) were classified as not involving a direct blow to the head at any point in the injury sequence.

4.3.6 Puck Possession

The category “puck possession” determined if the player had control of the puck, although not necessarily in direct contact with the puck, while attempting a hockey related skill (e.g., skating). Puck possession was broadly categorized as “with puck possession”, “just released the puck” or “no puck possession”. When considering the events (excluding fighting) that involved an opponent ($n = 158$), the player was in possession of the puck approximately 20% of the time (31-37 events; 20-23%); 35% (55 events) of the time the player had no possession of the puck. In 41-45% (65-70) of the events, the player who suffered a concussion had “just released” the puck; that is, the player was in possession of the puck at one time but was no longer in possession – they either shot or passed the puck – when the player was contacted by an opponent.

Of those classified as “just released”, 49 number of events permitted quantification of time-frames to analyze the time from puck release to contact. In over 70% of these events, the time from puck release to contact was less than 0.5 seconds.

4.3.7 Penalty

A final point of interest was to determine if the on-ice officials called a penalty on the play for the events that resulted in concussions. Of the events evaluated, we were able to determine whether a penalty was called for 166 events denominator. Of these, 29% were considered infractions according to on-ice officials. When looking specifically at direct contact to the head by shoulder, elbow, or gloves, 22% were deemed illegal actions.

4.4 Discussion

The aim of the present study was to understand how concussions occur at the NHL level in order to determine if a potential pattern(s) exist(s). With the combination of speed, hard surfaces, and frequent collisions in hockey, we expected that a proportion of hockey concussions would result from a collision with a teammate or accidental falls or trips; however, this proportion was minimal: accidental falls or trips and collisions with teammates accounted for only 10% of concussions analyzed. For the three and half seasons evaluated as part of this study, the predominant mechanism of concussion was consistently characterized by player-to-player contact, typically to the head by the shoulder, elbow, or gloves. When the principal mechanism was refined further, several

important characteristics were discernable: (i) contact was often to the lateral aspect of the head; (ii) the player who suffered a concussion was often not in possession of the puck; and (iii) no penalty was called on the play.

It is well accepted in the context of brain injury that injurious blows may result from direct (e.g., elbow-to-head collision) and indirect (e.g., shoulder-to-shoulder contact that results in abrupt deceleration without direct head contact) contacts. Despite the potential for injury in either case, most of analyzed events involved direct contact to the head (>70%), regardless of context (i.e., contact with a teammate, contact with an opponent, or fall / trip). Also, in the events where there was no direct impact to the head initially, contact to the head was often involved at some point in the injury sequence. Ultimately, less than 5% of the events analyzed did not involve contact to the head. Clinically, concussion is thought to occur even without direct head trauma, but in this sample, that occurred less than 5% of the time.

Regardless of the type of impact, the acceleration is thought to reflect the risk of brain injury. Linear and rotational head accelerations are influential for concussion during an impact. Ommaya and Gennarelli¹⁰⁷ were among the first to describe the linear and rotational accelerative mechanisms of injury in detail using animal models, and their seminal work suggested the rotational component was critical for the diffuse effects of head injury. It is thought that rotation about the brainstem produces shearing and tensile strains, resulting in brain injury.^{106, 127} The present study did not involve a detailed biomechanical analysis quantifying linear and rotational accelerations; however, the information distilled via video analysis suggests the predominant mechanism of a direct blow to the lateral side of the head often resulted in observable

rotation. This observation appears to concur with previous work identifying the possibly significant contribution of rotational acceleration.^{106, 127}

One of the most striking results from this study was that in the events involving player-to-player contact, greater than three-quarters occurred when the player was not in possession of the puck. “Not in possession of the puck” was comprised of two situations: (1) “No puck possession”, where the player was not in possession of the puck leading up to the contact with another player; or (2) “Just released”, characterized as the player having had possession at one point just prior to the contact with another player but no longer in possession. The latter situation is a time in which the player appears to be vulnerable. The hockey community often teaches players to “finish” their checks; however, an acceptable period of time for this action is not well defined before being considered an infraction. The regulatory bodies and officials may want to reconsider this currently acceptable behaviour of “finishing the check”, and at a minimum, educate athletes and coaches about the potential danger of injury [concussion] associated with it. It is imperative that coaches and players be aware of this period of vulnerability; players should not “let their guards down” at times when they may not necessarily be in contact with the puck (i.e., defensemen attempting to retrieve the puck in the corner or a player who has just passed or shot the puck).

It is important to highlight that in approximately 75% of the events analyzed, there was no penalty on the play. In other words, the behaviour that produced many of the concussions in our sample was not deemed to be illegal during game play. It is difficult to prevent such behaviour, and consequently concussions, if the behaviour is considered acceptable or part of the game. However, it is not appropriate to suggest

that the on-ice officials are at fault as this was beyond the scope of this study. Raters were not in any position of authority to determine if a penalty was warranted or not for the contact leading to concussions. Hockey is played at a high speed with a number of collisions taking place over the course of a game with acute injuries occurring in a split second, and at times, it is not an easy task during game play to discern if an infraction has occurred. In addition, if certain behaviours, such as incidental contact with an opponent's shoulder to a player's head were not called a penalty during play, then they would not be regarded as a penalty during the data collection period. As researchers, we had the luxury of slow motion in the video analysis process to fully evaluate and re-examine the events to distill the appropriate information. Nonetheless, given the clear mechanism of concussion in the majority of events analyzed in our sample, this finding calls into question whether the current rules and standards can be improved to safeguard players from potentially dangerous playing situations. Common sense would suggest that if the behaviour was sanctioned, we might expect that concussions resulting from direct blows to the head would be reduced. A number of leagues [e.g., International Ice Hockey Federation (I.I.H.F.), National Collegiate Athletic Association (N.C.A.A.), and Ontario Hockey League (O.H.L.)] have attempted to combat the escalating concern of concussions in hockey in this manner, and currently penalize all direct contacts to the head. However, to our knowledge, published data on the effects of such rules have not been reported to date.

It is encouraging to see the NHL has attempted to define unacceptable behaviour and ensure that officials implement the rules and standards of behaviour. Introduced in the 2010-11 season, Rule 48 "Illegal Check to the Head" states that "a lateral or blind side hit to an opponent where the head is targeted and/or the principal

point of contact is not permitted".¹²⁸ Combined with education, it is expected that over time, if players are aware that they will be consistently reprimanded for such actions, then they will be less likely to commit them. The concern about concussions is not specific to hockey and it is promising to see other professional sports introduce specific rules to reduce the risk of direct head contact. The National Football League (NFL) has recently enforced rules that address flagrant use of the helmet and which carry substantial financial penalties.

There has been research in a number of areas, all with similar objectives: reducing the frequency of concussions in hockey. One such area of interest is the use of protective equipment such as helmets or mouthguards. Historically, helmets have been successful in decreasing fatal and catastrophic head injuries because they prevent focal head injuries precipitated by direct trauma.¹²⁻¹⁷ However, current commercially available helmets are not designed well to prevent concussions. Nevertheless, helmet manufactures have begun to design helmets that incorporate distinct features meant to improve energy attenuation in response to lateral blows.¹²⁹ Also, the use of mouthguards has been suggested to provide additional protection, thereby reducing the risk of concussion, and various leagues require players to wear them. The benefit of such usage is that it provides protection against dental and orofacial injuries; however, at this time, there is little evidence that mouthguards provide protection against concussion.^{100, 101, 129} Other equipment modifications, such as softer elbow pads or shoulder pads, have been proposed to lessen the impact upon contact. Despite these improvements to equipment and rules enforcing their use, at this time, currently available protective equipment does not appear to be sufficient to prevent concussions in hockey.

Fighting accounted for fewer concussions than expected in the present study. Nevertheless, it is a proportion of concussions in which the mechanism is known and preventable through elimination of that act in hockey. However, some proponents of fighting believe that it has an integral place in our game, as fighting fulfills a "self-policing" function, and its removal may result in unintended consequences (i.e., increase in injuries, including concussions).

4.4.1 Limitations

Video analysis is a promising tool to analyze the mechanisms of specific injury types, and has been successful in a variety of sports (ACL in skiing, ankle injuries in volleyball, etc.).^{82, 83, 95, 114} However, when interpreting the results from the present study, some methodological issues need to be addressed. First, although this study provides a comprehensive evaluation of the mechanisms of concussion, its research design did not attempt to quantify the forces that produce brain injury. At this point, the relative contributions of linear and rotational accelerations to specific injury mechanisms have not been conclusively established.¹²⁷ There is promise in this regard; research investigating and quantifying linear and rotational accelerations by employing accelerometers in helmets is gaining popularity within the research community, which will hopefully produce better information with which to understand the nature of head impacts sustained by athletes (particularly in football and hockey). This growing body of work examining the influence of linear and rotational accelerations, combined with the results from the present study, will yield practical information that may improve safety in hockey and the larger sporting community.

The findings from this study revealed that a particular injury mechanism – direct blow to the head – accounted for a large number of events. However, those familiar with hockey have witnessed collisions that appear to involve significant forces applied directly to a player’s head, yet with no negative outcome (i.e., concussion). Meeuwisse¹³⁰ has suggested that it is important to measure and understand this “mechanism of no injury” (MONI), so that we can refine our understanding of which component(s) of the apparent mechanism of injury is (are) actually responsible for an injury. In addition, capturing and analyzing direct hits to head that do not result in concussion will allow us to understand the relative risk of such actions, thereby providing valuable information to our understanding of this potentially debilitating injury.

Finally, the present results were restricted to a dataset arising from video records corresponding to diagnosed concussions. Admittedly, we are uncertain of the existence and/or extent of failure to diagnose concussions in the NHL. Most researchers examining sport-related concussion agree that the overall rate of concussion for athletes participating in contact or collision sports is likely underestimated. That being said, the NHL currently has a comprehensive concussion program; we analyzed over 75% of concussions that occurred during the data collection period. Therefore, we are confident that the results are representative of concussions at the NHL level. It is also important to keep in mind that since we restricted our analyses to one particular league with its own set of rules and standards (e.g., in which face shields are optional; fighting is tolerated; touch icing), we are uncertain of the extent to which we can generalize our findings to other leagues and levels with different sets of rules across age groups.

4.5 Conclusion

Professional hockey is a complex contact sport involving a combination of strength, speed, and skill executed within an enclosed area. The potential for injury is inherent in the game, especially at the professional level. There have been great strides made in the design of protective equipment and rules enforcing their use; however, the most appropriate avenue to prevent concussions at this time is to change the behaviour of the players and those involved through rule changes. Based on the present results, it appears that preventing direct contacts to the head would have the greatest impact on reducing the number of concussions at the NHL level. This practical approach would not only include a rule to eliminate such behaviour but also significant discipline (e.g., suspension or fines) to act as deterrent and on-going education. It is important that the effects of any additions or changes to the rules moving forward warrant evaluation. The nature of the game of men's hockey as it is currently played, carries an inherent risk of concussion. This is the first study to our knowledge that has systematically assessed concussions using video analysis to code mechanism(s) of injury. As our understanding of the clinical consequences of head injuries has improved over the past decade, it is now imperative that we take the necessary steps to reduce or prevent their occurrence.

5 Chapter 5

5.1 General Discussion

A review of the literature over the past three decades indicates that significant advancements have been made in the clinical understanding of the natural history of concussion. Research has consistently reported that symptom and cognitive recovery occurs between 7-10 days for the majority of athletes following concussion.^{59, 87-91} However, a physiological understanding of the recovery mechanism remains less clear;⁶⁰ the few studies in this emerging area that have used advanced functional neuroimaging techniques suggest that physiological abnormalities can be identified beyond the resolution of physical symptoms and cognitive dysfunction.⁶⁰ It has also been shown that biochemical changes that occur in the brain following concussion can persist even after the person is asymptomatic, possibly resulting in a window of vulnerability during which the risk of further brain trauma is increased, unbeknownst to the injured person.⁷⁸ This is of particular concern because the evidence shows that serial concussions may have cumulative effects, even when individual injuries are apparently 'mild' in severity.^{131, 132} Furthermore, there is increasing evidence that concussions may predispose individuals to degenerative neurological conditions later in

life.^{80, 133-135} All of this suggests that athletes may unwittingly be subjecting themselves to unacceptable risks of brain damage and permanent impairment. The main purpose of this thesis was to systematically investigate, using video analysis, how concussions happen in NHL players, ultimately to generate hypotheses or recommendations to prevent concussions in the NHL as well as in other hockey leagues, at all levels of play.

In this concluding chapter, the principal scientific contributions of this thesis are summarized and their significance for understanding and preventing concussions in hockey are discussed. Additionally, lessons learned from the current body of work are discussed with a view to utilizing a systematic video analysis approach, developing future studies, and towards designing more effective prevention strategies.

The principal scientific contributions of this thesis may be summarized as follows:

- A reliable and objective recording tool that encodes for the majority of events leading to the injury situation (playing situation, player and opponent behaviour), as well as a description of mechanism of injury was developed and validated (Chapter 2).
- Several specific risk factors for concussion in NHL players, including: position, body size, specific locations on the ice, and particular situations based on a player's position were identified (Chapter 3).
- A common specific injury mechanism characterized by player-to-player contact and resulting in contact to the head by the shoulder, elbow, or gloves was also identified. When the principal mechanism was refined further, several important characteristics were discernable: (i) contact was often to the lateral aspect of the head; (ii) the player who suffered a concussion was often not in possession of the puck; and (iii) no penalty was called on the play (Chapter 4).

5.2 Video analysis research and Heads Up Checklist

The practical value of video replay is now well-established in hockey, from day-to-day use as a teaching aid or as a tactical tool to assist on-ice officials in the determination of a goal. From a research perspective, the widespread availability and use of video content lends easily to the investigation of many types of injuries, including concussions. Video analysis is not a novel approach to understand injury mechanisms; however, the current technological environment makes it possible for the majority of injuries in sports to be captured with visual resolution adequate to support a research environment that is far superior to what was available even five years ago. Even though the use of video is particularly well suited to describe the situational context and mechanism of injury, analysis of the content without a systematic framework and objective recording tool can potentially result in missing or biased information. Therefore, the fundamental first step of this thesis was to develop and validate the Heads Up Checklist (HUC), to ensure the tool was suitable for coding the relevant information related to concussions in hockey.

The process of developing the HUC was not without its challenges, as one of the aims of this study was to develop an objective recording tool that a naïve rater could potentially be trained to use with confidence and accuracy. Furthermore, we attempted to ascertain relevant and specific variables of interest and ensure that the categorical scales used for each variable were both highly representative of common situations and mutually exclusive, all within in a practical, user-friendly format. In the end, the HUC proved to be a reliable and objective recording tool that accounts for the situational

context (playing situation, player and opponent behaviour), as well as a description of mechanism of injury. Given the widespread availability and high quality of digital video records in other sports, it is reasonable to expect that the tool can be applied to various levels of play (e.g., university or collegiate), and with modification, adapted to address different injuries (e.g., ACL injury). Overall, a framework has been established to understand patterns of injury via video analysis. Consequently, we feel that the objective to develop the HUC was successfully met.

5.3 Summary of Main Research Findings

5.3.1 The four Ws of concussion

Who

The proportion of concussions resulting from a collision with a teammate or accidental falls or trips was minimal (<10%). With over 90% of concussions occurring as a result of player-to-player contact, initial results suggested many of the concussions were not the result of random, accidental events among players. Fights resulting in concussion accounted for only one tenth of the total number of concussions captured on video. One of the first objectives in the systematic analysis of concussions was to determine *who gets a concussion* (Chapter 3). The results suggested that forwards are at the greatest risk for concussion, as they accounted for significantly more concussions than their on ice representation.

When, Where, and under What circumstances

In addition to establishing which players (i.e., "who") get a concussion, it was important to consider when, where, and under what circumstances these injuries occurred. Concussions occurred most often in the first period, a finding that is contrary to the general trend of injuries in hockey.⁴¹ Since the majority of these injuries were in the first period and were characterized most often as direct contact to the head, it was suggested in Chapter 3 that some of these actions were related to a specific behaviour, possibly influenced by emotional intensity and/or strategic choices in the early stages of the game (e.g., "set the tone", "establish a forecheck", etc.).

The findings from the thesis indicated a relatively even distribution of perimeter and open ice events leading to concussion. Of importance, approximately one third (35%) of concussions involved direct head contact with boards or glass.

There is an obvious interaction between players' position and what they are doing on the ice. In evaluating the context of concussions, the results identified specific situational risks for forwards and defensemen. In particular, defensemen appeared to be at the greatest risk when retrieving the puck or behind the net. On the other hand, forwards were at the greatest risk when they were "on the rush".

5.3.2 Mechanisms of injury - How

Another important contribution of the thesis was the description of how player concussions occurred (Chapter 4). Concussions were often characterized by player-to-

player contact, resulting in contact to the head most frequently by the shoulder, followed by the elbow, and gloved hands (“gloves”).

In addition to characterizing the principal mechanism, several important characteristics were also discernable. First, contact was often to the lateral aspect of the head. Specifically, a large proportion (approximately 35%) of all concussions analyzed during the three and half seasons was classified as direct impact to the lateral aspect of the head by shoulders, elbows, or gloves. Second, the player who suffered a concussion was often not in possession of the puck (either classified as “just released the puck” or “no puck possession”). Finally, for the events that we were able to determine whether a penalty was called, over 70% of the incidents resulting in a concussion were not considered infractions by the on-ice officials.

5.4 Policy Implications

The nature and extent of the problem of concussion in sport has been delineated in Chapter 1. Over the past decade, there has been a significant increase in research highlighting the magnitude, scope, and consequences of concussion. In an effort to inform prevention strategies, the results from the studies in this thesis suggests that the most practical approach for reducing concussions was to attempt to modify the behaviour leading to direct contacts to the head. At this time, the NHL does not have a rule in place that prohibits all direct contact to the head by the shoulder; therefore, the most immediate and logical outcome would be the adoption of such a rule, similar to

many other leagues [e.g., Ontario Hockey League (OHL), Canadian Interuniversity Sport (CIS), National Collegiate Athletic Association (NCAA)].

This study was not an assessment on whether officials performed their duties correctly; however, with such a high percentage of events with no penalty on the play, examination of rules and corresponding enforcement warrants examination. Similarly, our results emphasize the importance of enforcing existing rules. In Chapter 4, it was highlighted that in approximately 75% of concussions analyzed, there was no penalty on the play; therefore, the behaviour that produced many of the concussions in our sample was not deemed illegal during game play. It is important to recognize that there are rules in place in the NHL that can influence acceptable behaviour. For example, it is unacceptable to travel a significant distance to violently check an opponent (i.e., Charging¹³⁶), and players are not allowed to contact an opponent such that the contact causes an opponent to be thrown violently in the boards (i.e., Boarding¹³⁷). Given the definitions of both of these penalties, there is merit in enforcing current rules and standards.

It may be somewhat presumptive to assume concussions in the NHL would significantly decrease if the adoption of a new rule and enforcement of existing rules were the sole methods of prevention. If a rule-based approach (with adequate enforcement) were the only solution, we would see an incidence rate much closer to zero than presently observed in the OHL, CIS, or NCAA. In fact, changing behaviour patterns is complex and likely requires a multi-pronged prevention strategy. For example, coupled with rule enforcement, greater potential for behavioural change exists

if illegal behaviour results in significant discipline. That is, if the behaviour is repeated by a player, the discipline should be far greater than the initial discipline.

An examination of infrastructure (playing environment) and advancements in equipment standards are also necessary avenues to explore in the reduction in concussions. With approximately half of the concussions occurring around the perimeter of the ice surface and one-third involving direct head contact with the boards or glass, structural standards of rinks need to be examined. The results from the thesis suggest that it would be useful to pursue a thorough examination of potential modifications with regard to player environment. Echoing our results, a recent public report by the Commissioner of the NHL owners indicated that facilities that currently have seamless tempered glass at the ends of the rink are required to switch to a safer Plexiglass system by the start of the 2011-2012 season.¹³⁸ The concern over playing environment was highlighted recently at the Bell Centre in Montreal, when a player was bodychecked along the boards and appeared to be seriously injured after striking a stanchion between the benches. This event resulted in a highly charged, negative emotional response by many fans, players, corporate sponsors, and government officials, and summoned the NHL's executive body to act to reduce the number of serious injuries.

The role of helmets is also often included in the discussion of ways to prevent concussions. However, at this time current standards for helmets¹³⁹ may be inadequate to prevent concussions given the modern day estimation of accelerations associated with concussions^{127, 129, 140, 141}. This is directly related to the lack of sufficient data

surrounding the biomechanical variables that cause a concussion injury. Significant efforts are currently underway towards this goal.^{127, 140, 141}

Education and awareness are another essential components of an effective concussion prevention strategy in hockey. Education and awareness consist of providing athletes with the basic information related to the potential short- and long-term consequences of concussions, and insisting that more has to be done with respect to player safety. A goal of such an initiative would be to shift the attitude of many of its participants. Consider the philosophy of a current NHL veteran: "We understand they have to take care of us, but at the same time, we choose to go out there and get hit and hit people. You understand it's just the way it is".¹⁴² However, "the way it is" requires a certain level of respect amongst players. It is important for current and future players to realize the need to change how one approaches the game. For instance, continuation of the hockey philosophy that encourages players to "finish" their checks when opponents are in vulnerable positions may no longer be valid in an era when safety becomes a greater priority.

5.5 Future Research

The findings from this thesis provide valuable information that could guide future research studies and generate additional research questions. One of the main findings from this work, highlighted in Chapter 4, revealed that a particular injury mechanism,

that is, a direct contact to the head, accounted for a large number of events. However, experience as a fan and spectator of the game suggests that not all significant forces directly to a player's head result in a concussion. Hence, an understanding of how frequently players engage in potentially injurious activities where the outcome is benign, i.e., where no concussion occurs, is required. Evaluation of the occurrence of concussion in a particular situation and caused by specific events, relative to the frequency of similar situations that do not produce concussions, would yield a statistic that can be used to determine the relative risk. For example, does every elbow to the head produce a concussion, or does a concussion occur x percent of the time in that situation? Not only is the knowledge of relative risk of such actions important, but also the mechanism of 'no injury' would prove valuable in refining our understanding of which component(s) of the apparent mechanism of injury is actually responsible for an injury.¹³⁰ A question of whether or not a specific action will produce an injury requires research into the physics of contact, and intrinsic factors that lead to vulnerability (e.g., biomechanical analysis of the characteristics of the individual and tissues, ligaments, examination of the tissues, other physiological factors that may affect the brain, availability of ATP to repair or overcome insult).

Many other leagues have introduced rules banning head-checking, yet the leagues that have taken a more strident approach with respect to rules still have concussions in their leagues. With a framework established to understand patterns of injury using video analysis, it would benefit other leagues at all levels of play to apply a similar approach to identify and describe concussions in their own context (e.g., women's hockey, at the youth level, university/collegiate, etc.); in turn, the information

ascertained at different levels and in different leagues could provide valuable information for future prevention strategies.

There is also potential to address additional research questions from the data generated from this thesis. Future analyses are warranted to explore possible relationships between various categories from the HUC, such as mechanism of injury (i.e., direct blow to the head), and collateral information, such as position played, length of time lost due to concussion, history of concussion, and type and length of symptoms. This work is already in progress: medical information obtained from the National Hockey League Injury Surveillance System (NHLISS) is being used to reveal such collateral data. In addition, future studies should consider evaluating the mechanism of injury from a descriptive perspective – using the HUC – in combination with kinematic and kinetic measurements. Kinematic measurement in this context generally involves sensors mounted on helmets to capture and quantify linear and angular accelerations. Kinetic measurement is the calculation of forces. The collective analysis could provide valuable insights into the causes and factors contributing to head loading and stresses on the brain.

The NHL introduced Rule 48 – Illegal Check to the Head, defined as “a lateral or blind side hit to an opponent where the head is targeted and/or the principal point of contact is not permitted”¹²⁸ – at the beginning of the 2010-11 season. The rule has received tremendous attention, including scrutiny by some on the grounds that it is insufficient for prevention of concussions at the NHL level. However, the rule has been in place for one season and data has not yet been analyzed. A policy evaluation study of Rule 48 is nevertheless important as it can lead to more concrete conclusions about

the causal impact of the rule. With respect to how to design such a study, an important component would be inclusion of pre-Rule 48 surveillance data on concussions to provide a context of historical trends. It is also important to identify other possible confounding factors (e.g., education initiatives, league wide awareness campaigns, other policies implemented, etc.) when interpreting the impact of the policy. A critical component in any evaluation of Rule 48 is gathering information about the individuals whose behaviour was influenced by the rule: the players. Not only would this process provide insight on whether the rule achieved its desired effects, but it would also determine how future policies may be created. In the end, rigorous evaluation of Rule 48 could affect the development of more effective policy and non-policy efforts to reduce concussions in hockey at the NHL level.

5.6 Conclusion

The methodological approach of using video analysis advances our understanding not only of the potential risk factors of concussions in hockey, but also about how concussions occur at the NHL level. Some of the results from the thesis have contributed to present-day prevention strategies (i.e., Rule 48) and will provide valuable information for future preventative measures. Unfortunately, it appears that significantly reducing the number and severity of concussions in hockey will be neither simple nor quick; the sport is best served by adopting a multi-pronged prevention strategy for dramatic change to take place. It is important to realize that hockey has evolved dramatically over the past 40 years and in its current form is almost unrecognizable from how it was played decades ago. Aside from the observable

differences in speed, skill, style of play and size of players, this is not the same game that was played without helmets, which was still permitted in the NHL as recently as 1997. If preventing concussion in hockey at the NHL is a priority, changes will have to occur at multiple levels: the culture of players, on-ice and off-ice discipline with infractions, assessment of infrastructure and equipment, and on-going education.

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- 142.** Kelly C. Bettman has it right with little change in game. *The Toronto Star*. March 19, 2011, 2011.

Appendices

Appendix A. Terms of Reference and Operational Definitions for Heads Up Checklist

Introduction

The Heads Up Checklist (HUC) is a tool that allows the user (the ‘rater’) to code video records of concussion events (‘clips’) into categorical information that can be analyzed as group data at a later time. The HUC is divided into several categories of information deemed by subject matter experts as being potentially relevant, antecedent factors contributing to the occurrence of a concussion.

Importantly, the HUC has no diagnostic utility; it is useful only after the diagnosis of concussion has been established. With appropriate training, the HUC should allow the rater to capture or rate the majority of the antecedent events leading to a concussive injury. However, there are two critical factors that directly affect the overall utility (and hence, the validity and reliability) of the HUC:

1. The quality of the clip and the replay technology. Generally, if the quality of the video clip is reasonably good (i.e., sharp acuity, with more than one angle, slow motion replays, etc.), the task of rating the video information can be relatively straightforward. Similarly, with computer replay technology, digitized video clips – even those of only a few seconds in length - can be analyzed in great detail. For the validation phase of the HUC, we used the DVD Player software resident in the Macbook Pro notebook computer (OS 10.4), which allows for real time and variable rate slow motion playback, as well as super slow motion or “step” playback, the latter allowing a stop-replay rate of ~20 frames per second. However, other DVD replay software might be equally acceptable, or perhaps better. The main point is that the task of rating video clips does not have to involve overly expensive technology.

2. The rater's familiarity with ice hockey. Although some of the situations captured by the HUC are easily discernible, even to the untrained eye (e.g., a mid-ice collision involving an opponent), some scenarios require the rater to make inferences that are not readily apparent and which require a certain familiarity with the game. For example, a player is checked and injured behind his own net, then gets up and skates to the bench. The camera remains focused on that player. Although none of the officials are visible in the clip, it is unclear whether a penalty was called or not. In examining the incident numerous times, it becomes apparent that the play shifts back and forth for a few seconds after the player is injured, and that the other team eventually has possession, with no whistle on the play. Therefore, the conclusion is that there was no penalty.

In short, it is felt that individuals familiar with hockey will be better suited to the task of rating clips. However, because the HUC forces the rater to complete all check boxes, and because most concussions in the NHL seem to occur within a finite range of circumstances, a naïve rater can still be trained-up to the task requirements.

The Terms of Reference and Operational Definitions booklet follows. The rater should refer to the content frequently, so as to become completely familiar with the terminology and situations.

General Procedures

1. Maintain Strict Confidentiality

The process of viewing and coding NHL video clips means that the players who are involved in concussion events (whether it is the injured player or others) will be easily identifiable to raters. Nevertheless, confidentiality of player identification must be maintained and only de-identified, coded man numbers are to be used on the HUC.

2. Clip Viewing

Experience has shown that the entire clip must be viewed in 'real time' more than twice and optimally several times in order to set the context of the event. This allows for the visual identification of the players involved and for basic information to be recorded on the HUC (e.g., Zone, Equipment, etc.). After the rater is comfortable watching the clip in real time, it should be watched in slow motion at least several times more. The clip should then be viewed in step slow motion sequence in order to determine the subtleties that might not be apparent in other modes. Once all of the checkboxes on the HUC are completed, the rater should then re-view the clip in real time to be satisfied that the information obtained is of high quality.

3. Attention to Detail

Viewing a clip of an injury can produce plenty of useful information, but sometimes subtleties can be overlooked. Be sure to watch the clip sequence from beginning to end several times because focusing on obtaining information for one check box might cause you to miss other information. For example, a player might not appear to be wearing a mouthguard after an injury, but as he leaves the ice, the camera shows him holding his mouthguard in his hand. In another example, it might not seem to be the case that a player is wearing a visor, but the reflective glare in a distance camera shot indicates he does in fact wear one.

Completing the Heads Up Checklist

General Information

“General Information” captures information related to the following:

Rater: The initials of the person coding the video clip.

Date: The date the clip was rated, using the yyyy/mm/dd format.

ID: The unique identification code assigned to the injured player, also referred to as the “Man Number”.

Game: Consists of **Regulation Play** plus **Overtime** (if required).

Period

Defined as a specified time frame consisting of 20 minutes in the National Hockey League (NHL). Regulation play consists of three stop-time periods.

First Period: First of three 20-minute stop-time periods.

Second Period: Second of three 20-minute stop-time periods.

Third Period: Final of the three 20-minute stop-time periods.

Overtime: Defined as a period of extra time played when the game is tied after the first three periods. In the NHL regular season, **Overtime** consists of a single extra time period that ends if either team scores, or ends at 5 minutes, whichever occurs first. During the playoffs, there is no time limit on overtime, which is played in 20-minute stop-time periods, or until either team scores.

Penalty

A rule violation, enforced by officials.

Yes: A penalty was definitely called for the contact that caused the injury.

No: No penalty called for the contact.

Inconclusive: It is not clearly apparent from the clip whether a penalty was called.

Score

A number that expresses the accomplishment of a team in a game or contest and distinguishes the winning team from the losing team.

Winning: The injured player's team was winning by a difference of 1 or 2 goals at the time of injury.

Losing: The injured player's team was losing by a difference of 1 or 2 goals at the time of injury.

Winning > 2 goals: The injured player's team was winning by more than 2 goals at the time of injury.

Losing > 2 goals: The injured player's team was losing by more than 2 goals at the time of injury.

Tie Game: The score was tied at the time of injury.

Inconclusive: It is not clearly apparent from the clip what the score was at the time of injury.

Event

The Event section captures some of the key information about the context in which the player was injured, including the mechanism of injury:

Scenario

Identify the context that precipitated the eventual injury. For example, did the scenario involve another player (e.g., With Teammate or With Opponent”) or an unprecipitated trip or fall (e.g., “Fall or Trip”); or was there no identifiable scenario that can be identified from the clip that precipitated the injury (“Inconclusive”). The operational definitions are as follows:

With Opponent: A player from the opposing team.

With Teammate: A player from the same team.

With Official: An individual enforcing the rules of the game, i.e., a referee or linesman. Attire includes black pants with black and white striped jersey; a referee is designated with an additional red and white armband.

Fall or Trip: Not precipitated by intentional or direct contact from another person on the ice surface.

Inconclusive: No definite result or conclusion based on video records.

Initial Contact With

Identify the body part (e.g., “Head”, “Elbow”, “Shoulder”, “Gloves/Fist”), or object (e.g., “Stick” or “Puck”) that first contacted the injured player in the Scenario (above). For example, a Scenario might involve an Opponent; and the initial contact to the injured player occurred when the opponent’s elbow struck the injured player in the face. In this case, Initial Contact With = elbow. The operational definitions are as follows:

Head: The uppermost part of the body containing the skull, eyes, ears, nose, mouth, and jaw.

Shoulder: The part of the human body between the neck and the midpoint of the upper arm (humerus).

Elbow: The joint comprising of the distal half of the humerus and the proximal half of the forearm (approximately above players’ gloves).

Gloves/Fist: Equipment used by hockey players, consisting of padding on the back of hands and extending over the wrist or exposed hand in a closed fist.

Stick: A piece of long handled equipment that includes the shaft and the blade. The blade might be curved.

Puck: The standard puck is a disk of vulcanized black rubber, 1 inch thick, and 3 inches in diameter.

Other: Does not fall under any of the above 6 categories e.g., knee or hip.

Not Applicable (N/A): Refers to unprecipitated trips or falls. For example, in a Scenario in which a player crossing the blueline loses his footing and then collides head first with the boards, the Scenario = “Fall or Trip” and the Initial Contact With = N/A (because the boards did not ‘strike’ the player).

Inconclusive: No definite result or conclusion. In this case, it cannot be determined from the clip how Initial Contact With occurred.

Region

Identify the anatomical region of the player receiving the contact. If the Initial Contact With = elbow, the player receiving the contact might be struck in the Head/Face, so Region = Head/Face. The operational definitions are as follows.

Head/Face: The uppermost part of the body containing the skull, eyes, ears, nose, mouth, and jaw.

Neck: The part of the human body superior of the sterno-clavicular joint and below the head.

Torso: The human body excluding the head, neck, and limbs.

Below Waist: Any region below the waistline (approximately below the iliac crest).

Inconclusive: No definite result or conclusion; so it is not clearly apparent from the clip where the injured player was first struck.

Location

This refers to the anatomical aspect of the Region struck. For example, if a player is struck directly in the Head/Face by an opponent's stick, then Location = Anterior. The operational definitions are as follows:

Anterior: Located towards the front or on the ventral surface of the body.

Posterior: Located behind or toward the rear of the body.

Lateral: Situated at or on the side of the body.

Inconclusive: No definite result or conclusion.

Acceleration of Head

This refers to the biomechanical plane(s) of the player's head motion that might have occurred during the Event. The operational definitions are as follows:

Sagittal or Coronal: Sagittal refers to the biomechanical plane that travels from the top to the bottom of the body, dividing it into left and right portions. Moving the head up and down (i.e., in a 'nodding' motion) would be moving in the sagittal plane. Coronal involves the biomechanical plane that divides the body into dorsal and ventral (back and front) portions. Trying to touch your ear to your shoulder would be moving the head in the frontal plane.

Transverse: The biomechanical plane that divides the body into cranial and caudal (top and bottom) portions. Rotating the head looking left or right would be moving the head in the transverse plane.

Multi-plane: The acceleration of head occurs in more than one plane. For example, a typical knock-out punch to the head would be associated in movement in both transverse and sagittal planes.

Inconclusive: No definite result or conclusion.

Note: *The following sections apply only to events exclusively involving forces to a player's head, after the initial Event has been evaluated.*

Secondary Contact

This section applies to physical contacts after the initial contact has been evaluated. For example, a player collides with an opponent while crossing the blueline and receives a Shoulder to the Anterior portion of the Head/Face. The player then falls, striking his head on the ice. If this occurs, the Secondary Contact = Ice. If the player had fallen and landed on his back, with no definite head strike, then Secondary Contact = N/A. The operational definitions are as follows:

Net: Consists of the goal posts extending vertically four feet above the ice surface and cross bar six feet long from one post to the top of the other post (including the netting enclosing the goal posts).

Ice: The frozen surface upon which the game of hockey is played on.

Skater: A member of either team or official participating in the game.

Boards: Structure consisting of fiberglass walls, the ledger board, and the glass that extends above the walls.

Not applicable (N/A): There was no observed secondary contact following the object of contact.

Inconclusive: No definite result or conclusion.

Tertiary Contact

This section applies to physical contacts after the secondary contact has been evaluated. For example, a player collides with an opponent at the blueline after both players strike heads. The first player then collides with a teammate, striking his head again (Secondary = Skater) and then falls to the ice, striking his head a third time (Tertiary = Ice). The operational definitions are as follows:

Net: Consists of the goal posts extending vertically four feet above the ice surface and cross bar six feet long from one post to the top of the other post (including the netting enclosing the goal posts).

Ice: The frozen surface upon which the game of hockey is played on.

Skater: A member of either team or referee participating in the game.

Boards: Structure consisting of fiberglass walls and the glass that extends above the walls.

Not applicable (N/A): There was no observed secondary contact following the object of contact.

Inconclusive: No definite result or conclusion.

Equipment

Visor

The front piece of the helmet, designed to protect the eyes, nose, and forehead. The hockey visor is most frequently composed of clear plastic or acrylic, although some players might use a metal 'cage' apparatus. The operational definitions are as follows:

Yes: The injured player's helmet included a visor.

No: The injured player's helmet did not include a visor.

Inconclusive: No definite result or conclusion.

Game Situation

The Game Situation section captures where the Event occurred, i.e., it describes the physical area in the rink where the player was injured.

Zone

The Zone is defined as any area of the ice rink consisting of offensive, defensive, and neutral areas. These are specifically defined as follows:

Defensive: The portion of the ice surface where the team is defending the goal net from the end boards up to and including the blueline.

Offensive: The portion of the ice surface from and including the blueline to the end boards furthest from the defended goal.

Neutral: Central portion of the ice surface located between the two bluelines.

Inconclusive: No definite result or conclusion.

Location

The Location is more specific than the Zone and includes the following areas:

Side Boards: Refers to the structure and area along the sides of the rink consisting of fiberglass walls, the ledger board, and the glass that extends above the walls up to and including three feet of ice surface towards the middle of the rink. The Side Boards end at the bend in each corner of the rink.

End Boards: Refers to the structure behind both goal nets of the rink consisting of fiberglass walls, the ledger board, and the glass that extends above the walls up to

and including three feet of ice surface towards the middle of the rink. The End Boards end at the bend in each corner of the rink.

Behind Net: The area behind both goal nets including below the goal line and including the trapezoid demarcated area.

Side of Net: The area to either side of the net, outside of the trapezoid demarcated area, but before the corner begins.

Corner: Refers to the rounded portion of the side boards connecting the side boards to the end boards. The corner also consists of the structure and area along the sides of the rink consisting of fiberglass walls, the ledger board, and the glass that extends above the walls up to and including three feet of ice surface towards the middle of the rink.

Open Ice: The area of the rink that is not categorized as side boards, end boards, corners, or behind the net.

Inconclusive: No definite result or conclusion.

Situation

The Situation describes the hockey specific actions during which the Event occurred.

The specific situations are operationally defined as follows:

Breakout: A player in the defensive zone is attempting to leave the zone with one or more teammates; at least one member of the team leaving the defensive zone must be in possession of the puck.

Backcheck: A defending player is attempting to return to the defensive zone while the opposition team is in possession of the puck.

On the rush: This occurs when a player or team has left the defensive zone, controls the puck, and moves through either the neutral zone and/or into the offensive zone in an effort to advance the puck closer to the net.

Forecheck: Occurs when a player in the offensive zone attempts to gain possession of the puck from a defender.

Transition: This describes the change in flow from defense to offense, after a defender gains possession of the puck setting up an offensive rush. The transition zone is located between the top of the circles in the defensive zone and bottom of the centre ice circle.

Retrieving puck: This occurs when a defending player attempts or is successful in gaining puck possession in the defensive zone. The area specified is from the bottom of the defensive zone circles, including both corners, end boards, and behind the net.

Other: Not captured by the above strategic plays.

Fight: A unique circumstance in which players remove their gloves and engage in fist fighting.

Inconclusive: No definite result or conclusion.

Puck Possession

Puck possession identifies if the injured player has control of the puck while attempting a hockey related skill. Puck possession refers to whether a player is judged to have had control of - but was not necessarily in direct contact with - the puck, while attempting a hockey related skill (e.g., skating). For example, a player stick-handling the puck on a rush is deemed to have control (and possession) of the puck, even if the Event occurs at the moment when the puck is off the player's stick (i.e., between stick-handle moves). However, the player who is checked before a pass arrives does not have possession. Finally, a player who passes the puck to a teammate and is checked within 2 seconds has Just Released the puck.

Yes: The player had possession of the puck.

No: The player was not in possession of the puck.

Just Released: The period of time (2 seconds) after which the player no longer has possession of the puck (e.g., following a pass, shot on net, or loss of possession to an opponent).

Inconclusive: No definite result or conclusion.

Anticipated Hit:

Refers to whether a player expected to engage in body contact.

Yes: The player was deemed to be aware and expected the body contact.

No: The player was deemed *not* to be aware and did not expect the body contact.

Inconclusive: No definite result or conclusion.

On-ice Medical Attention:

Provision of initial medical care to the player on the ice, performed by qualified medical professionals, most commonly team therapist/trainer or physician.

Yes: The player received on-ice medical attention.

No: The player did not receive on-ice medical attention.

Inconclusive: No definite result or conclusion.

Comments: Records other pertinent information in this section.

Rink Diagram: Mark the location of the Game Situation with an “X”

Appendix B. Heads Up Checklist (v 1.2)

HEADS UP CHECKLIST

ID: _____
RATER: _____

EVENT

SCENARIO:

- With teammate
- With opponent
- With official
- Fall or trip
- Other
- Inconclusive

INITIAL CONTACT WITH:

- Stick
- Head
- Gloves/Fist
- N/A
- Puck
- Elbow
- Shoulder
- Other
- Inconclusive

REGION :

- Head/Face
- Neck
- Torso
- Below Waist
- Inconclusive

LOCATION:

- Anterior
- Posterior
- Lateral
- Inconclusive

ACCEL. OF HEAD:

- Sagittal or coronal
- Transverse
- Multi-plane
- Inconclusive

Refers only to contact to head

SECONDARY CONTACT:

- Goal/Net
- Skater
- Boards
- Inconclusive
- N/A
- Ice
- Fist

TERTIARY CONTACT:

- Goal/Net
- Skater
- Boards
- Inconclusive
- N/A
- Ice
- Fist

EQUIPMENT

YISOR:

- Yes
- No
- Inconclusive

GAME SITUATION

ZONE:

- Offensive
- Defensive
- Neutral
- Inconclusive

LOCATION:

- 1 = Side Boards
- 2 = Corner
- 3 = End Board
- Behind Net
- Side of Net
- 4 = Open Ice
- Inconclusive

SITUATION:

- Breakout
- Backcheck
- On the Rush
- Forecheck
- Transition
- Other
- Retrieving Puck
- Fight
- Inconclusive

PUCK POSSESSION:

- Yes
- No
- Just Released
- Inconclusive

ANTICIPATED HIT:

- Yes
- No
- Inconclusive

ON-ICE MEDICAL ATTENTION:

- Yes
- No
- Inconclusive

GAME SHEET

PERIOD:

- 1st
- 2nd
- 3rd
- Overtime
- Inconclusive

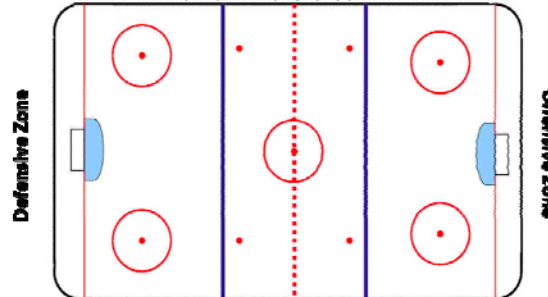
PENALTY:

- Yes - see comments
- No
- Inconclusive

SCORE:

- Winning
- Losing
- Winning > 2 goals
- Losing > 2 goals
- Tie Game
- Inconclusive

Mark an "X" of event on rink



COMMENTS:

PLEASE ENSURE ALL FIELDS ARE COMPLETED