11-19-2020 10:30 AM

The Impact of Impacts: Repetitive Head Impact Exposure in Canadian University Football Players

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A thesis submitted in partial fulfillment of the requirements for the Doctor of Philosophy degree in Kinesiology

Recommended Citation

Brooks, Jeffrey S., "The Impact of Impacts: Repetitive Head Impact Exposure in Canadian University Football Players" (2020). *Electronic Thesis and Dissertation Repository*. 7488.
https://ir.lib.uwo.ca/etd/7488

Abstract

Due to the physical nature of the game and repeated head impacts between players each play, the sport of football has one of the highest incidence rates of concussion. With nearly two million participants, this incidence rate translates to a reserved estimate of 100,000 concussions per year due to the contact nature of the sport. Injury thresholds have proven difficult to establish, so American football concussion research has shifted focus to measuring the accumulation of repetitive head impacts. As there are numerous rule differences between Canadian and American football, head impact exposure may present differently for Canadian players. Accordingly, the objective of this thesis was to investigate the effect of cumulative head impacts on Canadian university football players. This was achieved through three research projects using helmet-mounted sensors to monitor head impacts experienced by football players in practices and games, and measuring brain function via saccadic eye movements. Results illustrated that there were no differences in linear and rotational accelerations between striking and struck players during a collision. However, head impacts that occurred during kickoff plays experienced linear head accelerations that were double in magnitude and rotational head accelerations that were triple in magnitude than other special teams, offensive, and defensive plays (Chapter 2). Furthermore, the accumulation of head impacts significantly increased football players' saccade latencies, which persisted over two successive seasons (Chapter 3). The total number of head impacts experienced during their career was significantly affected by a player's position, and not their seniority (Chapter 4). In conclusion, this thesis identified football plays that resulted in high magnitude head accelerations, quantified the effect of individual head impacts on brain function using saccade latencies, and characterized career head impact exposure for football players. These results provide evidence that football head impact exposure needs to be reduced for the health of the players. Coaches and league administrators can use evidence-based research to employ strategies to reduce the number of head impacts to the sport of football.

Keywords

Football, concussion, head impacts, saccade, brain injury, linear, rotational acceleration.

Summary for Lay Audience

American football is one of the most popular sports to watch and play in North America, with over 100 annual million viewers and over two million participants. With its popularity has come the scrutiny regarding concussions and their short-term and long-term effects on player health and safety. Concussions are difficult to diagnose and unique to every individual. While one head impact may concuss a player, the same head impact may not have an effect on another player. Consequently, football research has shifted towards measuring the effects of overall head impact exposure in football athletes. Since there are numerous rule differences between Canadian and American football, head impact exposure may present differently for Canadian players than their American counterparts. Accordingly, this thesis investigated the effect of cumulative head impacts on Canadian university football players. Helmet-mounted, wireless sensors were used to monitor head impacts experienced by football players in practices and games. Rapid eye movements were measured before, during, and after the season to evaluate players' brain function. Results illustrated that there were no differences in head accelerations between striking and struck football players during a collision. However, head impacts that occurred during kickoff plays were significantly larger than other special teams, offensive, and defensive plays. Furthermore, the accumulation of head impacts significantly increased football players' eye movement reaction times, which continued over two successive seasons. A player's position, but not their seniority (freshman, sophomore, junior, senior, fifth year), significantly affected the total number of head impacts experienced during their varsity career. The results of this thesis provide evidence that football head impact exposure needs to be reduced for the health of the players. Coaches and league administrators can use evidence-based research to create strategies to reduce the number of head impacts to the sport of football.

Co-Authorship Statement

This thesis contains material from two manuscripts that are being prepared for submission (Chapter 2 and Chapter 3) and one submitted manuscript (Chapter 4) that encompass the collaborative work of researchers and co-authors. Jeffrey Brooks is the primary author of all of the chapters contained in this thesis. Dr. James P. Dickey (Professor in the School of Kinesiology, Faculty of Health Science, Western University) co-authored Chapters 2-4. Adam Redgrift (School of Kinesiology, Faculty of Health Sciences), Allen A. Champagne, Ph. D (Medical Student, Centre for Neuroscience Studies, Queen's University), and Dr. Douglas J. Cook (Associate Professor of Neurosurgery, Department of Neurosurgery, Queen's University) co-authored Chapter 2. Dr. Kody R. Campbell (Postdoctoral Fellow in the Department of Neurology, School of Medicine, Oregon Health and Science University), Wayne Allison (PhD student, School of Kinesiology, Faculty of Health Sciences), and Dr. Andrew M. Johnson (Associate Professor in the School of Health Studies, Faculty of Health Science) co-authored Chapter 4.

Acknowledgments

Dr. Jim Dickey – no amount of words, Starbucks cards, or funky socks can express my feelings of gratitude towards you. I can only hope that you recognize my growth as a researcher, writer, and a person have all been heavily influenced by you over the past six years. Your passion and support for your students is endless. It has been a privilege to have learned so much from you, and I hope you take as much pride from this thesis as I do.

Biomechanics labmates, past and present, and other friends I have made during my career as a university student. To name but a few: Dr. Ryan Frayne, Dr. Alexandra Harriss, Will Smith Jr., Jenna Schulz, Emilie Woehrlé, Marquise Bonn, Gordon Barkwell, Wayne Allison, and Dillon Richards. You have all been a part of what has made my time at Western a highlight of my life. You made it a joy to come to work each day. Thank you.

This research could not have been completed without the support of Paul Walker and Gerry Iuliano of GForce Tracker. You guys are awesome and I enjoyed our annual AFCA trips. Thank you for always being available to help troubleshoot the devices!

To the members of the 2009-2019 Mustang football teams, and assorted coaching staff during that time, especially Greg Marshall and Jeff Watson – you guys are all family to me. I will miss the locker room talk, the grueling workouts, and bus trips. I am proud to be a Mustang.

Mom and Emma. You both are such strong and beautiful women. Emma, I am proud to call you my sister and brag about you whenever the opportunity arises. Mom, I would not be the man I am today if it wasn't for you. I love you both so much.

My fiancée, Olivia. You make me smile and laugh even when (I think) I do not want to. You are always by my side and have been endlessly supportive in my research. You have helped me find my way when I was overwhelmed. Your willingness to help and be involved in one way or another has encouraged the pride I feel in this research. I cannot wait until I can call you my wife.

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Chapter 1

1 Introduction

A sport related concussion is a traumatic brain injury induced by biomechanical forces that may be caused either by a direct blow to the head or a blow to the body that results in an impulsive force transmitted to the head.[1] This brain injury presents differently between individuals, and between concussions. Indicators of a possible concussion include signs, symptoms (somatic, cognitive, and emotional), balance impairment, behavioural changes, cognitive impairment, and sleep disturbance.[1] Most individuals will recover in 10-14 days, however some symptoms may persist for longer periods, perhaps indefinitely.[1,2] This is important since approximately 94,000 Canadian youths and adults experience a concussion each year.[3] Furthermore, in 2018, 93% of sport-related brain injury emergency department visits in Canada were due to a concussion.[4] In the United States, the Centers for Disease Control and Prevention referred to the prevalence of concussion in sport as a "silent epidemic" in a report to the US Congress.[5]

Due to the physical nature of the game and repeated head impacts between players each play, football has one of the highest incidence rates of concussion per athletic exposure compared to other sports.[6] With nearly two million participants,[7–9] this incidence rate translates to a reserved estimate of 100,000 concussions per year due to football. In line with the incidence of concussions, research about sport related concussions has predominantly focused on the sport of football. In an effort to understand the mechanism of injury, numerous football studies have measured biomechanical variables involved in concussive head impacts.[10–15] Specifically, linear and rotational acceleration thresholds have been investigated. One research team analyzed video of 31 helmet impacts between professional football players and reconstructed those impacts using instrumented test dummies in a laboratory setting.[16] They measured an average linear acceleration of 98 g and rotational acceleration of 6432 rad/s^2 in concussive impacts. Another study used the kinematic data measured in the aforementioned reconstructed head impacts as inputs for a finite element model of the brain.[15] They proposed linear injury thresholds of 66, 82, and 106 *g*, and rotational injury thresholds of 4600, 5900, and 7900 rad/s^2 for 25%, 50% and 80% probability of a concussion, respectively. While informative, these proposed thresholds were limited as they were based on video analysis, physical testing using instrumented test dummies, and computer modelling. Measurements from in-game data are required to validate these thresholds.

Helmet mounted sensors allow for the measurement of kinematic variables such as linear and rotational acceleration during football play. Measurements from helmet mounted accelerometers evaluate the helmet's motion rather than the head of the player wearing it.[17] Algorithms translating helmet data to head centre of mass data are required for comparable measurements to laboratory studies.[17,18] A plethora of studies have instrumented football players' helmets and recorded data during concussive impacts. The linear accelerations of these impacts range from 55-178 *g* and the rotational accelerations range from 163-15,397 rad/s^2.[12,13,17–21] The wide range of measured helmet data does not support the proposed thresholds calculated from laboratory measurements. The broad range, and combinations of high and low linear and rotational head accelerations, illustrate that there is no universal threshold for concussive injury.[10] They also bring into question whether linear or rotational kinematics play a larger role in the mechanism of injury, or if it is the combination of linear and rotational kinematics that is damaging to the brain.[22]

The lack of a universal threshold for concussions indicates that lesser magnitude impacts may also cause damage to the brain. The cumulative effects of these smaller magnitude, repetitive head impacts have been studied at all levels of football with varying results. Studies of youth,[23,24] high school,[24–30] and college football[31,32] measured significant changes in brain structure in players who did not suffer a concussion over the course of a season. Other studies collected head impact measurements over the course of a football season and did not observe any differences in preseason and postseason scores on neurocognitive tests.[33–35] The ability to quantify the effects of repetitive head impacts appears to be influenced by the approach used to measure changes in the brain. Imaging studies have quantified these structural brain changes while neurocognitive tests may not be sensitive enough to measure them.[36,37]

While imaging studies are able to measure structural changes in the brain in absence of clinically diagnosed concussion, the associated costs, time requirement, and limited access to equipment and facilities reduce their utility.[38] A more portable and cost-effective method of measuring repetitive head impacts is needed. Additionally, a method that can be administered in a time-efficient manner will allow for more regular data collection to determine the acute changes rather than changes over an entire season. Some studies have measured significant increases in blood biomarkers[39] and near point convergence[40,41] - a measure of the eyes' ability to converge on a target where higher scores are indicative of convergence insufficiencies - due to repetitive head impacts in as short a time frame as a single practice. While blood biomarkers are invasive and expensive to analyze, examining changes in oculomotor function such as near point convergence or saccadic eye movement could prove effective and time efficient.

Rapid eye movements, called saccades, are a valuable tool for examining brain function. The two main types of saccadic eye movements are prosaccades and antisaccades. Prosaccades are the most frequent action an individual performs on a daily basis and involve the voluntary movement of the eyes towards a stimulus.[42] Antisaccades, on the other hand, involve the suppression of the automatic response to look towards the stimulus and instead generate a prosaccade in the opposite direction. Antisaccades are associated with longer latencies and more directional errors than prosaccades.[43,44] The ability to control voluntary eye movements by suppressing the urge to look at a stimulus, and choosing to look in the opposite direction, involves the brain exhibiting executive control.[44] Executive function allows for decision making, situational adaptation, and focusing on relevant information; all important factors for team sport athletes[45] like football players who possess more proficient executive control over their motor systems than non-athletes.[46]

Individuals with concussions exhibit deficits of executive-related tasks.[47] Accordingly, the antisaccade task has been used to differentiate between concussed and healthy individuals. For example, numerous studies report longer antisaccade latencies (ranging from 37-93 ms) and directional errors in acute concussed individuals compared to healthy controls.[48–55] At 30 days post concussion, individuals do not exhibit significantly different saccade latencies from healthy individuals.[48,51,54,55] However, as is often the case in concussion studies, cross-sectional data from concussed individuals are compared to healthy group data as baseline measures are often not collected. Concussed individuals vary in their baseline measures[56] and therefore subtle differences may not be captured when analysis focuses on group data.

Some studies have measured changes in oculomotor function due to repetitive head impacts. Soccer players exhibited significantly slower reactions on an Anti-Point task (similar to antisaccades, but with the added gross motor element and the complexity of hand-eye coordination) immediately following a bout of purposeful heading compared to controls.[57] Another study measured significant increases in near point of convergence in high impact football players compared to low impact football players over the course of five team practices,[40] in the absence of concussion. In the same study, measurements three weeks postseason did not exhibit any differences from baseline in the high impact group. This study was part of a longitudinal study that measured increases in near point convergence up until the middle of the season, after which it returned to baseline levels.[58] Thus, the oculomotor system has adequate sensitivity to be able to document the deleterious effects of repetitive head impacts. However, to the best of our knowledge, studies have not measured saccade latencies in combination with repetitive head impacts over the course of a football season, or differences between baseline measures in successive seasons.

The accumulation of repetitive head impacts has been associated with cases of the neurodegenerative disease chronic traumatic encephalopathy (CTE) in football athletes.[59–61] A diverse cohort revealed a prevalence of CTE in approximately 6% of the general population,[62] while an 88% prevalence of this disease has been documented in football players, including 91% specifically in college football players.[61] However, these samples have been criticized as suffering from selection bias.[63,64] A recent study found that the risk of developing CTE increases by 30% for every year of tackle football participation, and doubles every 2.6 years of participation.[65] Accordingly, monitoring and reducing head impacts in football is paramount to a player’s long-term health. However, most studies that examine head impact exposure extrapolate estimates based on years of participation,[60,65–67] a single season of head impact data,[23,26,68–71] or player self-reported head impact exposures.[72] Few studies have quantified head impact exposure in multiple football seasons.[73–75] Furthermore, it is important to consider player position as there are differences in head impact exposure between different football positions.[69,73–76] For example, linemen will experience more head impacts, and lower magnitude impacts, than wide receivers and running backs.[69] A player's seniority on the team is also an important factor in head impact exposure as it may be associated with factors such as amount of playing time and drills in practice. This issue of seniority was investigated in one study which reported reduced brain activation along the midline in senior players compared to freshmen during an auditory oddball task.[77] Rather than estimating or extrapolating head impact exposure, collecting head impact data over a player's career would provide definitive head impact exposure data.

While much of the focus of football research has been on individual concussive impacts, or overall head impact exposure during a season of play, there remains an understudied area of head impact research: the kinematics involved in non-concussive head impacts between two football players has yet to be explored. Aspects of the game of football, such as the type of impact between two players and the identification of plays that are associated with more severe head impact magnitudes, are important considerations for minimizing the risk of head injury in football players.

The head kinematics for striking[78] and struck players[79] are described in other papers within the series evaluating laboratory reconstruction of head impacts. Only 27 impacts were reconstructed, with a focus on concussive injuries (n=22). All concussive injuries occurred in struck players. Struck players had significantly higher magnitudes of linear and rotational head accelerations compared to striking players, regardless of whether the impact resulted in a concussion or not. Another study used finite element modelling of reconstructed laboratory head impacts and determined that head impact location has a large effect on brain injury.[80] While these studies of reconstructed head impacts have demonstrated differences in head impact magnitudes between striking and struck players, as well as the influence of head impact location on brain injury, they are limited as they are based on laboratory reconstructions using instrumented test dummies, not real football players.

Head impacts reconstructed in a laboratory setting are idealized and controlled. Head impact measurements from sensors that occur during football could yield different results than those measured in a laboratory setting. A study of college football players confirmed that struck players experience greater rotational accelerations compared to striking players.[81] They also established that impact location affected head impact severity for striking and struck players, similar to the finite element modelling study. However, this study only evaluated one of the players in each impact event – either the striking or the struck player. Head impact magnitudes of the striking and struck player may differ if they are measured from the same collision.

The vast majority of football studies examine American football players. There are notable differences between the Canadian and American football games which could affect head impact magnitudes. In the Canadian game, the field is larger, players can be in motion before the snap of the ball, teams have one fewer attempt to achieve a first down, and there is an extra player on the field for each team. A larger field size and players in motion before the snap of the ball may result in larger head impact magnitudes due to longer closing distances between striking and struck players. Since teams have one more player and one less set of downs, the Canadian game typically involves more passing plays than the American game. A pass-first offensive scheme is associated with higher magnitude linear and rotational head accelerations than a run-first offense.[82] The fewer number of downs also results in more special teams plays, as teams often punt the ball to change field position on third down. Higher magnitude head impacts occur during special teams plays than offensive or defensive plays.[83] However, these measurements have not been made in the Canadian game.

1.1 Overall Purpose

The overall objective of this thesis is to investigate the effect of cumulative head impacts on Canadian university football players. This was achieved through three projects using helmet-mounted sensors to monitor head impacts experienced by football players in practices and games, and measuring brain function via saccadic eye movements.

1.2 Chapter 2 Purpose

To measure kinematic head impact magnitudes between striking and struck Canadian university football players and determine specific football plays and impacts that result in high magnitude linear and rotational head accelerations.

1.3 Chapter 3 Purpose

To determine if cumulative head impacts in Canadian university football players affect saccade performance over the course of a playing season, and if effects persist between seasons.

1.4 Chapter 4 Purpose

To quantify head impact exposures for Canadian university football players over their varsity career and how impact exposure is affected by number of athletic exposures, position, and seniority.

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Chapter 2

2 The Hammer and the Nail: Biomechanics of Striking and Struck Canadian University Football Players

2.1 Introduction

Concussion research focuses on people's health and safety - whether it be diagnosis, treatment, or prevention. In an effort to better understand the mechanism of injury, studies have examined the sport of football due to the sport's prevalence of head impacts and concussions.

Football studies have examined biomechanical variables related to the mechanism of injury to gain a better understanding of concussions. Injury thresholds and cumulative impact exposure risk have been proposed and varied conclusions of no injury threshold[1], probability percentages for concussion[2], incidence predictions based on position[3] and session[4], and lack of cumulative effects[5] have been made. Many studies have migrated their focus to quantifying head impact exposures; collecting head impact data from football players over extended periods of time.[6–10] While purposes and results of these studies vary, a common understanding is that the more severe the head impact, the greater risk for injury to the brain.[5,11,12] To better understand the mechanism of injury, some studies have focused at the individual impact level. Identification of plays and parts of the football game that are associated with more severe head impact magnitudes is essential to minimize risk of head injury in football players.

One study reconstructed professional football impacts in the lab, determined average head kinematics for striking and struck players, and reported them in separate papers.[13,14] They reconstructed a relatively small number of impacts from video (n=27) and focused on impacts that resulted in concussive injury. Furthermore, they only evaluated helmet-to-helmet collisions, and none of the striking players suffered concussions in these impacts. Thus, the results of this study are not generalizable to other levels of play and provide limited information about non-concussive head impacts. Some studies used finite element modelling to determine brain strains from laboratory head impact reconstructions.[15–18] These studies determined that head impact location has a large effect on regional brain strain.[18] Nevertheless, these studies of reconstructed impacts have illustrated differences between players delivering the impact and receiving the impact, as well as the influence of head impact location on brain injury.

In contrast to laboratory reconstructions, it is relatively straightforward to collect large data sets of actual football head impacts in games using wearable sensors. A college football study instrumented football players with sensors and determined that player anticipation did not affect head impact severity, and that struck players experience greater rotational accelerations compared to striking players.[19] In agreement with the finite element modelling studies, they also established that impact location affected head impact severity for striking and struck players. However, this study only evaluated one of the players in each impact event – either the striking or the struck player. The researchers acknowledged that head impact measurements may differ if both players involved in a collision were measured. However, to the best of our knowledge, no studies have reported impacts between two instrumented players.

All previously mentioned studies examine American football players. The Canadian game of football has several rules that set it apart from the American game which could influence head impact magnitudes. The field size is larger (CAN=110 x 65yds, US=100 x 53yds), players can be in motion before the snap of the ball, there is one fewer attempt to achieve a first down (CAN=3, US=4), and there is one more player on the field for each team (CAN=12, US=11). The larger field size and players in motion may result in larger head impact magnitudes due to a potential for larger closing distance between the striking and struck player.[20] As well, due to the fewer number of downs and more players on the field, the Canadian game typically involves more passing plays; a pass-style offensive scheme is associated with higher magnitude head accelerations than a run-style scheme.[21] Additionally, the fewer number of downs results in more special teams plays, where higher magnitude impacts occur than on offensive or defensive plays.[20] Accordingly, it is important to evaluate the magnitude of head impacts in Canadian football as American data cannot be generalized to the Canadian game.[6,22–24]

The purpose of this study was to measure kinematic head impact magnitudes between instrumented striking and struck Canadian university football players. We hypothesized that struck players will experience higher head impact magnitudes than striking players, tackling collisions will result in larger head impact magnitudes than blocking collisions, head impact magnitudes will vary by location on the head, and that special teams plays will experience higher head impact magnitudes than offensive or defensive plays.

2.2 Methods

2.2.1 Participants

Select members of two Canadian university football teams that were part of larger studies at each location were eligible for this study. Other components of these studies have been published.[6,25] This study was approved by both local research ethics boards, and all participants provided informed consent. The two teams faced each other once during each Fall USports regular season of play in 2017 and 2018. A total of 156 unique players competed in these games, 94 of whom were equipped with a helmet-mounted sensor. The participants in this study had to have experienced a head impact with an opposing player, and both of the players had to be equipped with sensors. All impacts were verified on video to establish a ground truth dataset, a suggested best practice for helmet-mounted head impact sensors.[26–28]

2.2.2 Helmet Instrumentation

The GForce Tracker (GFT) was used by both teams to measure helmet impacts (Artaflex Inc., Markham, ON, Canada). One GFT was attached to the inside of each participant’s helmet, right of the crown cushion, using an industrial-strength recloseable fastener (3M^{TM} Dual Lock^{TM} Recloseable Fastener SJ3551 400 Black, St. Paul, MN). Previous studies have used[23,25,29–31] and validated[29] this location and mounting. The GFT triggered when the helmet linear acceleration exceeded the user-defined threshold. This study used a threshold of 15 *g*, which is consistent with best practices.[32] Each impact was time stamped and recorded to the device’s onboard storage.

2.2.3 Impact Data Protocol

The GFT data were transferred to a laptop after each game and then uploaded to GForce Tracker's cloud-based storage. A summary file describing every impact (time stamp, peak linear acceleration, peak rotational acceleration, and helmet location) were later downloaded for analysis.

Data reduction extracted the peak linear acceleration and peak rotational acceleration for each head impact. Similar to previous research,[29] the peak resultant linear acceleration and peak resultant rotational acceleration at the centre of mass of the head were estimated using a correction algorithm based on impact location dependent equations.

2.2.4 Video Data Protocol

Game video was recorded and analyzed using a Sony Vixia HD camera (EVS25, Endzone Video Systems, Sealy, Texas, United States). Game time and time of day were recorded for each game to match sensor time stamps to game video. Each game was uploaded to a video analysis software program (dba HUDL, Agile Sports Technologies Inc., Lincoln, Nebraska, United States). The game videos from both seasons were reviewed using the video software tool.

Only head impacts between players instrumented with helmet sensors were analyzed. Head impacts were first identified via video and confirmed with matching helmet sensor time stamps. Each collision between two players was given a unique identifier to identify impacts between specific pairs of players. Each impact was classified according to the player, play type, impact type, player involvement, opposing player impacted, and position by a single rater using a standardized rubric created for this study. Player positions were defined as defensive backs, linebackers, defensive and offensive linemen, running backs, quarterbacks, and wide receivers. Impact type was either tackle or block. Play type consisted of pass and run for offensive and defensive plays, and field goal, punt, punt return, kickoff, and kick return for special teams plays. Player involvement categorized impacts into striking or struck actions. A player was classified as struck if an opposing player hit them. A player was classified as striking if they initiated the collision with their opponent. During impact observations, the rater was blinded to the head kinematic data.

2.2.5 Statistical Analysis

A Shapiro-Wilks test was used to determine the normality of the head impact magnitude distributions. Normally distributed parameters are reported as mean and standard deviation, and non-normally distributed parameters are reported as median and interquartile range. Age, mass, and height of participants were measured at the start of the football season.

All statistical analyses were performed in R,[33] with linear mixed effects analyses conducted using the lme4[34] and lmerTest[35] packages. Two linear mixed effects models were created. One evaluated linear acceleration while the other evaluated rotational acceleration. The fixed effect of player involvement separately interacted with the fixed effects of impact type, game scenario, and impact location within both the linear and rotational acceleration models. Random effects of players involved in each collision were included in both models to account for player and positional differences across both teams. Impact locations were front, back, right and left on the helmet. Treatment contrasts were used to compare each level of fixed effect to the reference level.

Post-hoc analyses were conducted using Tukey multiple comparison tests from the emmeans package.[36] Statistical significance was defined using a threshold of 0.05. Effect sizes in linear mixed effect modelling can be misleading and inaccurate,[34] and therefore are not calculated.

2.3 Results

Head impact data were collected from 58 players [age: 21.9 (1.7) years, mass: 100.8 (17.5) kg, height: 186.0 (5.6) cm], including defensive backs (n=11), linebackers (n=14), defensive (n=10) and offensive linemen (n=7), running backs (n=8), quarterbacks (n=1) and wide receivers (n=7), representing 21 players from one team and 37 players from the other team. A total of 1085 impacts were recorded via helmet sensors. Of which, 276 (25.4%) video-verified collisions with matching head impact data were analyzed.

Overall, the median linear head acceleration experienced by players was 13.9 (14.7) g and the median rotational acceleration was 740.2 (1095.3) rad/s^2.

When the impacts were examined as a whole, there were no significant differences in linear ($F_{1,447} = 0.37$, $p = .54$) or rotational acceleration ($F_{1,454} = 1.02$, $p = .31$) between striking and struck players (Table 2.1). There were also no significant interactions between player involvement and impact type for linear ($F_{1,104} = 3.22$, $p = .08$) or rotational acceleration ($F_{1,140} = 0.20$, $p = .66$, Table 2.1). There was a significant interaction between player involvement and impact location for measures of rotational acceleration ($F_{3,524} = 4.36$, $p = .005$) but not linear acceleration ($F_{3,521} = 1.13$, $p = .34$, Table 2.1). Post hoc testing revealed that collisions to the back of the head had larger angular accelerations than collisions to the front ($t_{523} = 2.99$, $p = .02$) and left ($t_{515} = 3.50$, $p = .003$) of the head for the striking player.

Table 2.1 Mean Linear and Rotational Head Accelerations of Canadian Varsity Football Player for Player Involvement Across Entire Study, and the Interactions with Impact Type and Impact Location

	Linear Acceleration (g)				**Rotational Acceleration (rad/s^2)**			
		95% CI				**95% CI**		
	Mean	**L**	**U**	***p***	**Mean**	**L**	**U**	***p***
Player Involvement								
Striking[a]	22.2	17.7	26.7	(Ref)	1737.7	1284.4	2191.1	(Ref)
Struck	21.7	17.3	26.1	.85	1466.8	1022.6	1911.0	.36
Impact Type								
Block								
Striking[a]	22.6	18.1	27.1	(Ref)	1663.5	1212.2	2114.7	(Ref)
Struck	19.2	14.7	23.8	.24	1319.8	869.0	1770.7	.23
Tackle								
Striking[a]	21.9	16.2	27.6	(Ref)	1812.0	1232.7	2391.4	(Ref)
Struck	24.2	18.6	29.7	.53	1613.7	1051.2	2176.3	.60
Impact Location								
Striking								
Back[a]	18.5	12.4	24.6	(Ref)	2340.2	1726.1	2954.2	(Ref)
Front	20.8	16.0	25.7	.81	1553.0	1062.7	2043.4	.02[b]
Left	23.5	18.0	28.9	.33	1319.9	773.4	1866.5	.003[b]
Right	26.1	20.6	31.6	.06	1737.9	1188.8	2286.9	.20
Struck								
Back[a]	13.4	7.6	19.2	(Ref)	1159.5	580.6	1738.4	(Ref)
Front	22.2	17.3	27.1	.003[b]	1601.0	1110.6	2091.4	.29

Left	24.4	19.1	29.7	< .001^{b}	1348.3	818.2	1878.4	.89
Right	26.8	21.5	32.2	< .001^{b}	1758.4	1222.9	2293.8	.14

[a] Denotes the reference category used for post hoc testing.
[b] Significantly less than reference category.

There was a significant interaction between player involvement and play type for measures of linear acceleration ($F_{6,265} = 3.23$, $p = .004$) and rotational acceleration ($F_{6,280} = 3.10$, $p = .006$). Striking players experienced significantly greater linear head accelerations during kickoff plays than field goal ($t_{303} = 3.48$, $p = .01$), kick return ($t_{265} = 3.19$, $p = .03$), pass ($t_{251} = 3.12$, $p = .03$), punt return ($t_{248} = 3.20$, $p = .03$), and run ($t_{247} = 3.46$, $p = .01$) plays. Struck players did not experience significantly different linear accelerations between any play types. Striking players experienced greater linear accelerations than struck players during kickoff plays ($t_{267} = 3.30$, $p = .001$). Struck players experienced greater linear accelerations than striking players during kick return plays ($t_{274} = 3.01$, $p = .003$, Figure 2.1).

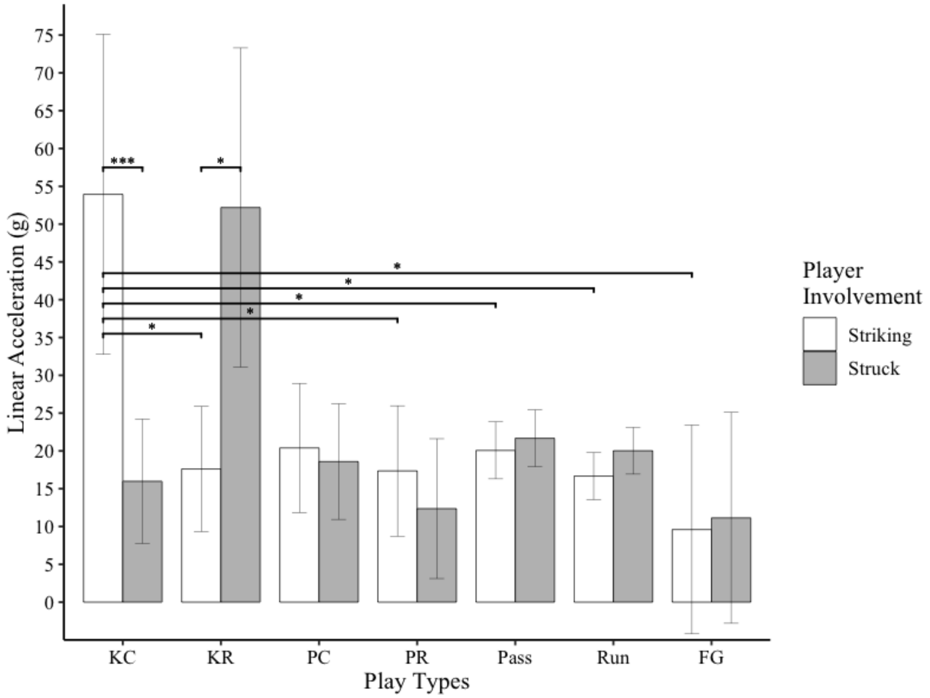

Figure 2.1. Bar graph of linear head acceleration for striking and struck players during different types of football plays. Error bars indicate 95% confidence intervals. * indicates p < .05. *** indicates p = .001. KC = kickoff cover; KR = kickoff return, PC = punt cover; PR = punt return; and FG = field goal.

Striking players experienced significantly greater rotational head accelerations during kickoff plays than field goal ($t_{328} = 3.38$, $p = .01$), kick return ($t_{290} = 3.18$, $p = .03$), punt return ($t_{274} = 3.15$, $p = .03$), and run ($t_{272} = 3.45$, $p = .01$) plays. Struck players did not experience significantly different rotational accelerations between any play types. Striking players experienced greater rotational head accelerations than struck players during kickoff plays ($t_{291} = 3.30$, $p = .001$). Struck players experienced greater rotational head accelerations than striking players during kick return plays ($t_{300} = 2.67$, $p = .008$, Figure 2.2).

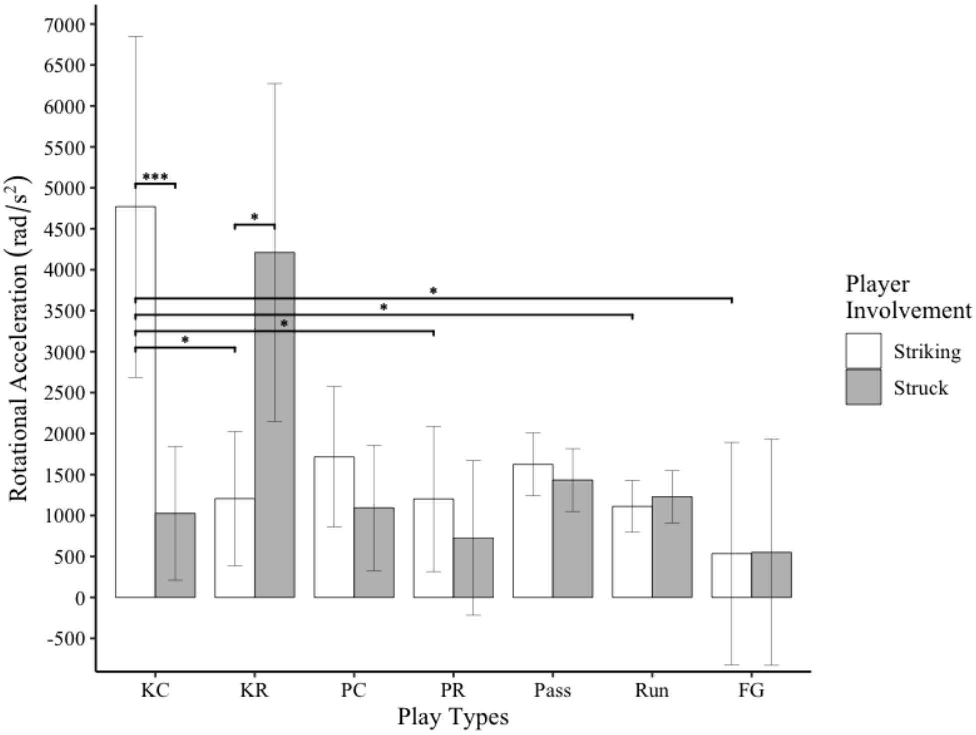

Figure 2.2. Bar graph of rotational head acceleration for striking and struck players during different types of football plays. Error bars indicate 95% confidence intervals. * indicates $p < .05$. *** indicates $p = .001$. KC = kickoff cover; KR = kickoff return, PC = punt cover; PR = punt return; and FG = field goal.

2.4 Discussion

The purpose of this study was to measure kinematic head impact magnitudes between instrumented striking and struck Canadian university football players. We hypothesized that struck players will experience higher head impact magnitudes than striking players, tackling collisions will result in larger head impact magnitudes than blocking collisions, head impact magnitudes will vary by location on the head, and that special teams plays will experience higher head impact magnitudes than offensive or defensive plays. In contrast with our hypothesis, we did not observe any statistically significant differences in linear or rotational acceleration between striking and struck Canadian university football players when all impact and play types and locations were considered. Similarly, in terms of impact type, we did not observe any statistically significant differences in linear or rotational accelerations, for both striking and struck players, between blocking and tackling. Striking players experienced greater rotational accelerations for impacts to the back of the head than the front of the head. Kickoff plays exhibited greater linear and rotational head accelerations than most other plays for the striking player. Finally, kickoff plays exhibited significantly larger linear and rotational head accelerations for striking players than struck players, while kick return plays exhibited significantly larger linear and rotational head accelerations for struck players than striking players.

The median linear and rotational head accelerations for striking and struck players reported in this study are lower than measurements in other similar studies. Four other studies have measured head impact magnitudes in Canadian university football players using the same head impact sensor.[22,24,25,37] However, only one of them used a location-dependent algorithm to calculate centre of mass impact magnitudes from the helmet shell measurements[22] which reduces the mean absolute percent error of peak linear and rotational accelerations measurements from 50% to less than 10%. The other studies only report raw measurements.[24,25,37] The study that used the correction algorithm reported average game impact magnitudes of 21.53 *g* and 1846.4 rad/s^2, which are comparable to the measurements from our study. The research team that recreated professional level impacts in a laboratory setting using instrumented test dummies measured significantly higher linear and rotational accelerations in the striking (56.1 *g*, 3983 rad/s^2) and struck (89.4 *g*, 6272 rad/s^2) players.[13,14] However, the majority of these impacts resulted in concussion in the struck players, and were measured from elite athletes so are not generalizable to university football studies. A similar study of American university football players[19] measured slightly higher linear and comparable rotational accelerations in the striking (24.5 *g*, 1401 rad/s^2) and struck

(25.1 *g*, 1502 rad/s^2) players than those measured in our study. The study with American football players did not include offensive or defensive linemen in their data set. This is important since linemen have lower magnitude impacts than other positional groups,[8,21,38] as well as a lower number of extreme impacts (impacts greater than the 95th percentile of the data set) per 1,000 impacts.[7–9,22] The addition of linemen to our study sample likely increased the number of low magnitude impacts, thereby decreasing the average magnitudes of measured linear and rotational head accelerations. Finally, a study examining differences in play types measured similar linear (25.2 *g*) and rotational accelerations (1442 rad/s^2) in special teams plays[20] than the special teams plays measured in our study.

Previous research has observed greater rotational head accelerations in the struck player than the striking player, and no differences in linear acceleration.[19] While our data did not exhibit any statistically significant differences between striking and struck players for either linear or rotational head impact parameters, the confidence intervals for the struck player are almost twice as large as the striking player. This dispersion of data implies that some of the impacts in the struck players were higher magnitude than the striking player.

While this study is similar in design and player cohort to a study examining striking and struck player head impact magnitudes in American college football,[19] an important distinction must be made. As is pointed out in their study[19], head impact data was only collected from one player for each collision. Thus, the impact magnitudes may have differed for the striking and struck players as they were collected from different collisions. Our study only compared head impact magnitudes between striking and struck players from the same collision. Accordingly, we were able to draw meaningful comparisons between striking and struck players since they were based on the same collision.

Our hypothesis that tackling collisions would result in larger head impact magnitudes than blocking collisions was not supported. However, we noted blocking styles differed depending upon the play type. In offensive and defensive plays, linemen or running backs engaged with defensive players in close quarters to prevent them from reaching the ball carrier. Defensive players had to react to the play, allowing offensive players to position themselves in between the defensive player and the ball carrier to block them. In special teams plays, the play was more spread out due to the field position change from kicking of the ball. Additionally, linemen are not usually involved in special teams plays. Accordingly, there were larger closing distances between faster players, which has been attributed to larger head impact magnitudes.[20] Taken together, there may be a larger difference between blocking and tackling collisions than what we measured. Additional data is required to investigate this phenomenon.

Striking players experienced greater rotational accelerations for impacts to the back of the head than the front of the head. This can be explained by the striking player's fast forwards motion of the head when they contact an opponent's body, but do not engage their own helmet. The forwards motion often measures as an impact location to the back of the head due to the sudden peak linear acceleration measured by the accelerometer in the anterior direction.

Special teams plays have been identified as higher risk, with higher linear and rotational head accelerations measured in collisions with larger closing distances.[20] Our measurements indicate significantly increased linear and rotational head accelerations on special teams plays compared to pass and run plays on offense and defense, specifically during kickoff and kick return collisions. In the Ivy League of the National Collegiate Athletic Association, kickoffs accounted for 6% of all plays but 21% of concussions.[39] Accordingly, the kickoff has been highlighted as one of the most dangerous plays in football. We observed linear accelerations for this play that were twice as large as any other play type, and triple as large for rotational accelerations as any other play type, supporting the concept that kickoff plays are dangerous. The kickoff has undergone rule changes in the recent past. These include the removal of three person "wedges" on the kick return team (three players link arms to form a barrier between other players and the ball carrier), restricting the kickoff team to a five yard run to the line of scrimmage, and moving the line of scrimmage forward to encourage more touchbacks (when the ball is kicked into the opposing team's end zone and play is stopped).[40] While there have been ongoing changes to kickoff rules in the American game,[39,40] it is apparent that similar changes should be made in the Canadian game to reduce head impact severity for all players.

This study does not come without limitations. One team only had a subset of players instrumented with accelerometers while the other team had all players instrumented. Thus, not all impacts between players were measured. The measurements made in this study are not representative of an entire Canadian university football game, however we believe they are still comparable due to similarities with other studies.[19,20] This study only measured head impacts from players on two teams in two different seasons. Different coaching schemes influence head impact exposures,[21] so the results of this study may not be generalizable to other teams of different coaching styles. This study used a linear acceleration threshold of 15 *g* to prevent recording accelerations from normal activities,[41] which is consistent with best practices.[32] Other studies have used a 10 *g* recording threshold,[7,19,30,42–44] which increases the number of measured head impacts and average magnitude of the impacts.

While no differences between striking and struck players during tackling and blocking were measured in this study, we did observe significant differences for kickoff plays that are particularly meaningful. Linear head accelerations for kickoff plays were double that of other special teams, offensive, and defensive plays and rotational head accelerations were triple. Canadian university football should follow actions taken in American college football to change rules around kickoff plays to make the game safer for its players.

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Chapter 3

3 Effect of Repetitive Head Impacts on Saccade Performance in Canadian University Football Players

3.1 Introduction

Concussion research has gained prominence following the discovery of chronic traumatic encephalopathy (CTE).[1] Initially multiple concussions were thought to be the cause, but recent research has shown that CTE is associated with repetitive head impacts, not concussions.[2,3] While a single concussion can cause acute damage to the brain, individuals usually recover within 30 days.[4] Repetitive head impacts, like those experienced in contact sports, are more frequent than concussions and over time have been linked with cases of CTE from football, hockey, and boxing athletes.[2,3,5]

Some studies have examined the short-term effects of repetitive head impacts. Imaging studies have identified changes in brain structure in as little as one season of contact sport.[6–9] On the other hand, studies have reported no difference in neurocognitive tests between preseason and postseason,[10–12] but these tests may not be adequately sensitive.[13,14]

Oculomotor function – specifically saccadic eye movement – has successfully differentiated between concussed individuals and healthy controls.[15–20] Prosaccades are the automatic response to look towards a stimulus. Antisaccades are the suppression of this automatic response and generation of a saccade in the opposite direction of the target.[21] Accordingly, the antisaccade task tests inhibitory control and the ability to generate voluntary actions - indicators of executive control.[22] Executive function allows a person to make decisions, adapt to situations, and pay attention to relevant information. This is important in everyday life, but in particular for team sport athletes,[23] where it has been established that college football players possess more proficient executive control over their motor systems than non-athletes.[24]

Therefore, the purpose of this study was to determine if cumulative head impacts in Canadian university football players affect saccade performance. We hypothesized that saccade latencies and number of errors will increase with cumulative head impacts.

3.2 Methods

3.2.1 Participants

Varsity football team members of the Fall 2017 and 2018 USports (Canadian intercollegiate) football seasons were eligible to participate in this prospective cohort study. Western University's Health Sciences Research Ethics Board approved the protocol and all participants provided informed consent. Of the 144 unique players on the varsity football team over these two seasons, 127 players were included in this study as they completed a baseline and at least one subsequent saccade test. A subset of 61 players participated in both seasons (Table 3.1).

Table 3.1. Participant and Data Demographics

Characteristics	Participants (n=127)
Age, mean (SD), years	20.8 (2.0)
Mass, mean (SD), kg	98.3 (18.4)
Height, mean (SD), cm	184.6 (5.9)
Head Impacts, Total No.	77,707
Testing Sessions, No. (%)	864 (95.9)[a]
Saccade Trials, No. (%)	31,397 (99.1)[b]

[a] 37 sessions were missed due to player injury, removal from team, or scheduling conflict.
[b] Trials displaying an anticipatory response or missing data accounted for 0.94% of trials and were excluded from analysis.

3.2.2 Helmet Instrumentation and Impact Data Collection

The GForce Tracker (GFT) was used to collect head impact data (Artaflex Inc., Markham, ON, Canada). The GFT triggered when a linear acceleration exceeded the user-defined threshold. This study used a threshold of 15 *g* which is consistent with best practices.[25] Each impact was time stamped and recorded to the device's onboard storage. One device was adhered to the inside of each participant's helmet, right of the crown cushion, using a recloseable fastener (3M™ Dual Lock™ Recloseable Fastener SJ3551 400 Black, St. Paul, MN). This location and mounting are similar to previous studies[26–29] and have been validated.[30]

Participant attendance was documented for each practice and game. Impacts were discarded if they did not occur in drills during practices and did not occur when participants were on the field during games. The GFT data were transferred to a laptop after each athletic exposure for analysis.

3.2.3 Saccade Apparatus and Procedure

Saccades were collected in four testing sessions during the season. Baseline and preseason tests were performed before and after training camp, respectively. A midseason test occurred after the fourth of eight regular season games. A final test was completed after playoffs concluded. In the second season, a fifth testing session was included after the regular season ended, before playoffs (Table 3.2).

With the room lights on, participants sat at a table (height 77.5 cm) with their head placed in a fixed head-chin rest throughout saccade testing. Visual stimuli were presented on a custom-made light board centred on the participant's midline and located at a 55 cm viewing distance. Light emitting diodes (LEDs) were embedded in a stimulus board and covered with black stereo cloth. A LED (48 cd/m^2) located at participants' midline eye level served as the fixation point, and LEDs located 15.5° left and right of the central fixation LED served as target stimuli, consistent with other studies.[31,32] Each trial began with the illumination of the fixation LED which signaled the participant to direct their gaze to the central fixation. The target LED was presented (50 ms), serving as the signal to initiate the prosaccade or antisaccade, following a randomized fore period (1000-2000 ms). The fixation LED was visible throughout the trial (no-gap paradigm).[33] Photodiodes captured light from the LEDs to determine the desired saccade's timing and direction. Prosaccades and antisaccades were completed in separate blocks. The target location was pseudo-randomly ordered (pick without replacement) to ensure that each block contained 10 left and 10 right targets.

Different saccade measurement approaches were used in the two seasons. In the first season, a high-speed digital video camera (Exilim EX-FH20, Casio, Tokyo, Japan), placed directly in front of the participant above the light board, recorded the participant's eye movement at a 210 Hz frame rate with a 480 by 360-pixel image. Fibre optic cables (Simplex 1.0 mm Industrial Fiberoptics, Tempe, AZ, USA), in series with the light board, were secured in the camera field of view to record the timing of the target light on the video system.[32]

In the second season, electro-oculography (EOG) was used to capture participants' saccade latency and direction.[34–37] Participants were fitted with three disposable surface electrodes (AM-N00S/E, AMBU Blue Sensor Adhesive Snap Electrode, Ambu Inc, Glen Burnie, MD, USA) placed at the outer canthi of each eye and the centre of the forehead. The voltages from the electrodes were amplified and filtered using an isolated electrophysiological amplifier (Model 2024F, Intronix Technologies Corporation, Bolton, Ontario, Canada) and sampled at 1000 Hz with a 16 bit analog-to-digital converter (USB 6211, National Instruments, Austin TX) using a custom LabVIEW program (LabVIEW 2011, National Instruments, Austin TX). Signals were displayed in real time on a computer to monitor signal quality. Although different saccade measurement approaches were used in the two seasons, they yield comparable saccade measurements.[36,38]

Table 3.2. Mean Number of Head Impacts, Total Test Sessions Completed and Saccade Errors during Two Consecutive Football Seasons

	Preseason	**Post Training Camp**	**Midseason**	**Post Regular Season[a]**	**Post Playoffs**
Mean number of impacts (SD)	0	82.1 (94.2)	218.0 (204.3)	264.8 (215.9)	414.9 (351.2)
Saccade sessions completed	191	190	182	93	171
Total number of errors from all saccade trials	266	332	240	181	180

[a]Post Regular Season test only occurred in second season.

3.2.4 Video Data Analysis

Video data from the high-speed camera was rated using QuickTime Player (version 7, Apple Inc., California, USA). Eye motion onset was identified by the initial horizontal displacement in the pupil after the stimulus light. Saccade latency was determined as the number of frames from onset of stimulus light to onset of eye motion. This approach for quantifying saccades using high-speed video yields comparable saccade latencies and errors as those measured by an eye-tracker system.[32]

3.2.5 EOG Data Analysis

The raw saccadic EOG voltages were post-processed using a custom LabVIEW program. The EOG voltages were band-pass filtered from 0.05 to 20 Hz using a second order Butterworth filter.[39] An onset detection algorithm[40] was used to determine the start of each trial from the photodiode signal, and each saccadic eye movement onset from the EOG signal. The latency was calculated as the difference in timing between the onsets of the target LED and the EOG signal. The EOG signal voltage polarity was used to determine saccade direction. Trials with an anticipatory response (i.e., latency < 100 ms[41]) or missing data (e.g., no target light visible in video recording, participant blinked) were excluded from subsequent analysis.

3.2.6 Statistical Analysis

All statistical analyses were completed using R.[42] Descriptive statistics for saccade latency and number of errors are reported as mean and standard deviation. Age, mass, and height of participants were measured before training camp.

To identify predictors of a player's saccade latency throughout a season, a linear mixed effects model was used with cumulative head impacts and saccade type (prosaccade or antisaccade) entered as fixed effects. Due to differences during time of season and variability amongst individual players, test session and individual differences were modeled as random effects with a random slope of saccade type. Days between head impact and test completion was a covariate in the model. To determine the model-of-best-fit for the latency data, three separate models were tested: null hypothesis, saccade type effects, and saccade type and cumulative head impacts effects. The null model consisted of saccade latency predicted by the covariate and random effects. The saccade type and cumulative head impacts models tested these factors as fixed effects, and the interaction model added the intersection of saccade type and cumulative head impacts to the prediction equation. In evaluating the goodness-of-fit among the models, the saccade type and cumulative head impacts models were compared with the null model. The interaction model was compared with the model in which saccade type and cumulative head impacts were allowed to predict saccade latency without interacting.

Differences among fixed effect levels were tested using *t*-tests, evaluated with a Satterthwaite degrees of freedom approximation.[43]

A similar process was used to examine differences between baseline saccade latencies in successive seasons. Baseline measurement sessions, saccade type, and cumulative head impacts were inputted as fixed effects. The null model was determined by the random effects of player variability with a random slope of saccade type. To identify the contributions of our fixed effects, we fit successively more restrictive models to the data, and determined the extent to which the models improved the prediction.

Finally, linear mixed effects models were used to examine the effect of cumulative head impacts on total saccade errors during the saccade tests. The number of days between last head impact and date of test completion was used as a covariate in the null model, with a random effect of player variability. Fixed effects of time and cumulative head impacts were tested to evaluate whether they improved the model prediction.

All mixed effects models were evaluated using the lme4[44], lmerTest[45], and car[46] packages. Treatment contrasts were used to compare each level of fixed effect to the reference level. Experiment-wise alpha was held to 0.05 for all comparisons.

Minimal clinically important difference (MCID) was used to evaluate the meaningfulness of the observed differences. It was calculated using the effect size-based approach.[47] Specifically, the baseline standard deviation was multiplied by 0.2 to calculate the MCID in saccade latency corresponding to a small effect size.

3.3 Results

The standard deviation of saccade latencies at baseline was 62.06 ms, and therefore the MCID in saccade latency was 12.41 ms. Antisaccade latencies were longer than prosaccade latencies; a statistically significant and meaningful increase of 26.86 ms (95% CI [25.62, 28.10], $t_{31270} = -42.43$, $p < 0.001$, $d = -0.48$, Figure 3.1).

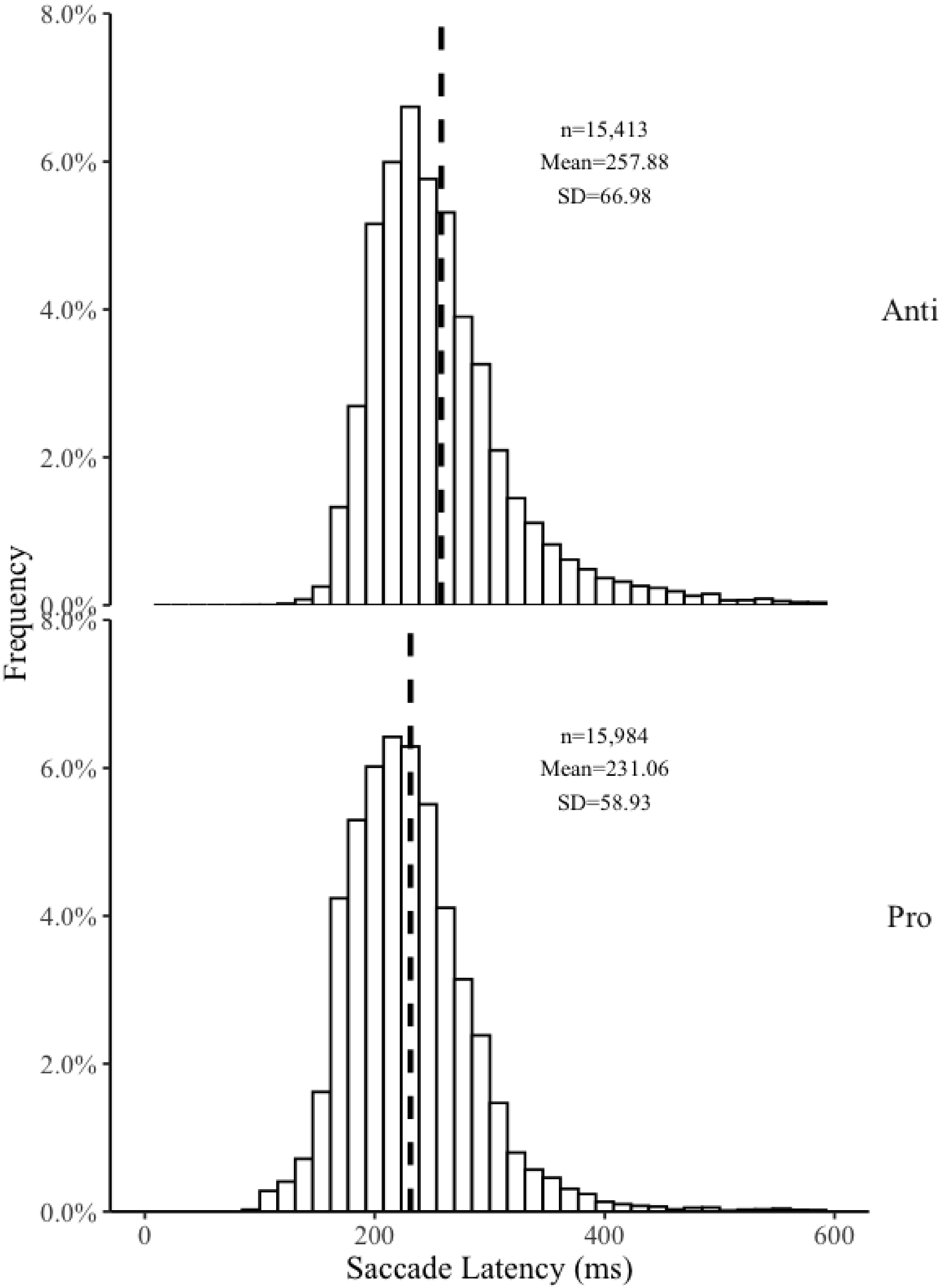

Figure 3.1. Frequency distribution of all correct prosaccade and antisaccade latency trials performed by varsity Canadian football players over two consecutive playing seasons. Mean latency is indicated by the dashed line. Antisaccade latencies were significantly longer than prosaccade latencies ($p < .001$).

The mixed effects model evaluating saccade latency revealed that the fixed effect of saccade type improved the null model significantly ($\chi^2_1 = 130.35$, $p < .001$). The addition of cumulative head impacts further improved the saccade type fixed effect model ($\chi^2_1 = 5.14$, $p = .02$). This model revealed that each head impact increased saccade latency by 5.27×10^{-3} ms (95% CI [7.16×10^{-3}, 9.82×10^{-3}], $p = .02$, Figure 3.2), despite the test date during the season. An interaction between cumulative head impacts and saccade type did not significantly improve the prediction model ($\chi^2_1 = 0.76$, $p = .38$).

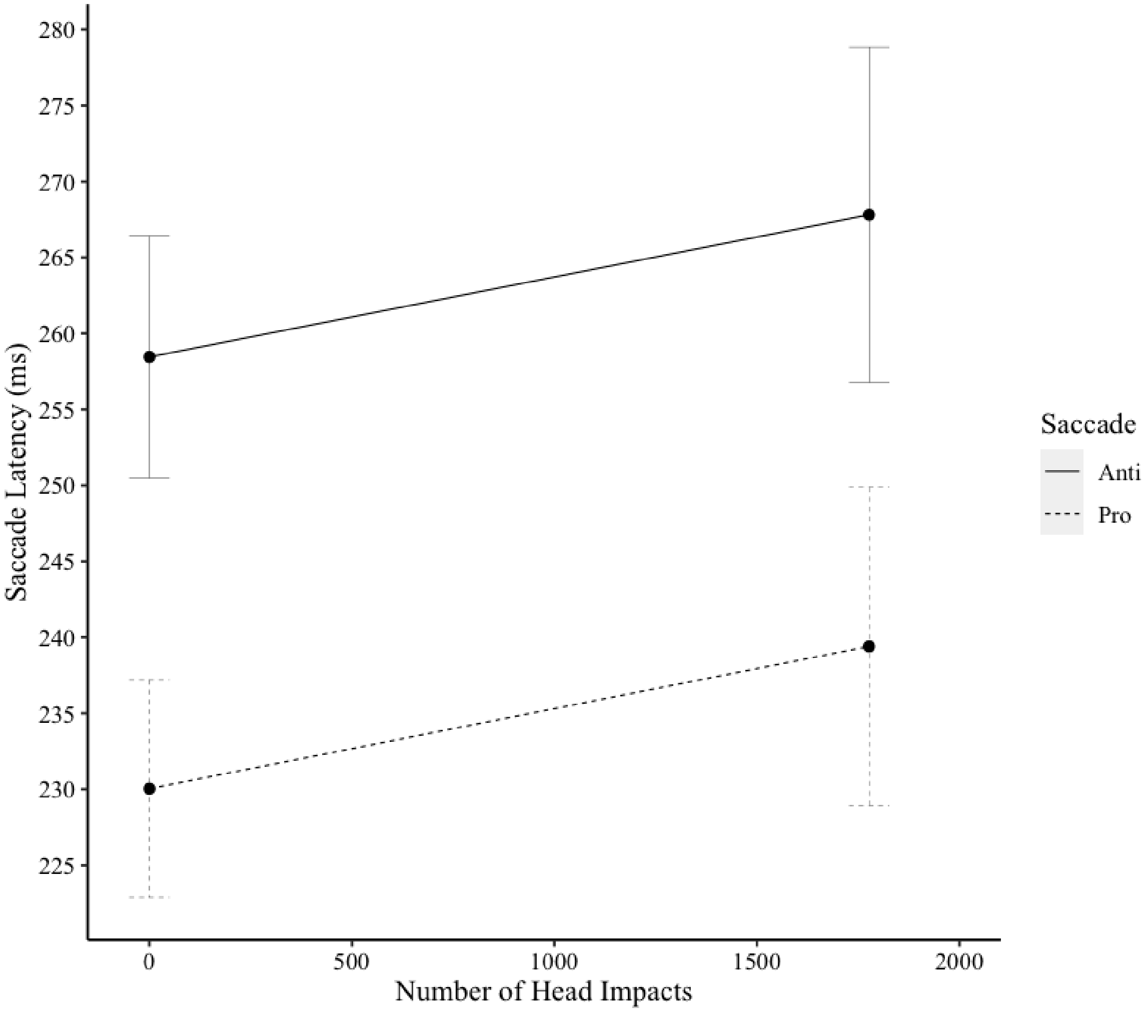

Figure 3.2. Prosaccade and antisaccade latency differences according to number of head impacts sustained during a season of Canadian varsity football. Solid lines indicate antisaccade latencies, dashed lines indicate prosaccade latencies. Error bars indicate 95% confidence intervals.

The mixed effects models evaluating saccade latency at baseline for the 61 players who participated in both seasons indicated that test and saccade type had a statistically significant effect on saccade latency prediction ($\chi_1^2 = 23.64$, $p < .001$, $\chi_1^2 = 47.36$, $p < .001$). When combined together, both fixed effects significantly improved the saccade latency model ($\chi_2^2 = 70.56$, $p < .001$). Saccade latencies were 10.82 ms (95% CI [7.71, 14.17], $p < .001$, Figure 3.3) longer at the 2018 baseline measurement than at the 2017 baseline measurement, which is below the level of change considered to be clinically meaningful. Cumulative head impacts did not produce a statistically significant better fit to the data than the model with test and saccade type ($\chi_1^2 = 0.05$, $p = .82$).

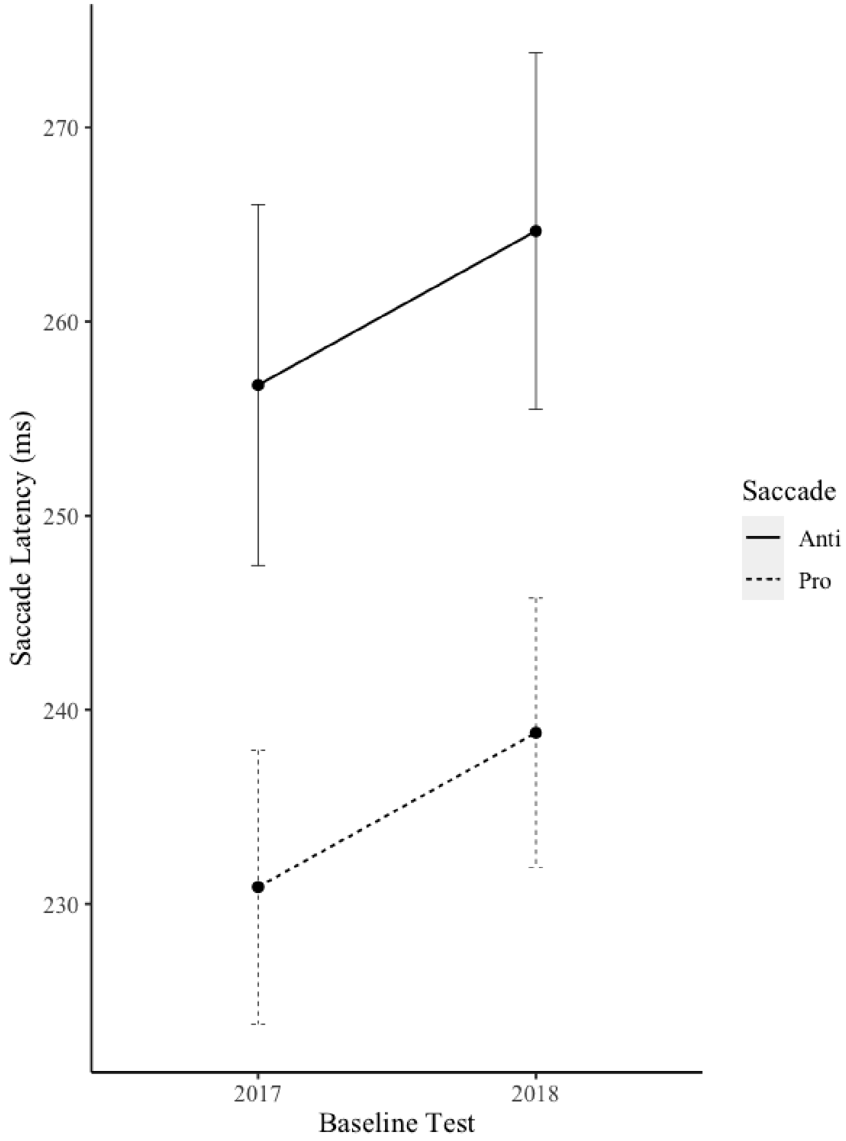

Figure 3.3. Prosaccade and antisaccade latencies between baseline measurements in successive Canadian varsity football seasons. Solid lines indicate antisaccade latencies, dashed lines indicate prosaccade latencies. Error bars indicated 95% confidence intervals.

The mixed effect model evaluating total errors indicated that time had a statistically significant effect on total errors made during the saccade trials ($\chi^2_4 = 10.22$, $p = .04$). There were 0.67 more errors made during saccade trials after training camp than after playoffs ($t_{708} = 3.02$, $p = .02$). There were 0.87 more errors made during saccade trials after the regular season than after playoffs ($t_{727} = 3.22$, $p = .01$). Cumulative head impacts did not produce a statistically significant better fit to the data than the model with time ($\chi^2_1 = 0.08$, $p = .78$).

3.4 Discussion

Saccade latency increased by 5.27×10^{-3} ms for each impact a Canadian university football player received to the head. Additionally, players who participated in both seasons showed a statistically significant but not meaningful increase in baseline saccade latency from the first season to the second. Cumulative head impacts did not significantly affect the number of errors made during saccade trials.

Players in this study experienced a similar number of head impacts per season as reported in numerous university football head impact exposure studies.[26,28,48–50] A player’s position significantly determines impact magnitude and frequency.[26,49,50] Even within positional groups, a player’s number of head impacts can vary depending upon seniority and roster depth.[28] This study measured saccade latencies of all roster depths at different positions, including injured players who did not experience any head impacts. Accordingly, position was not differentiated in the analysis.

A study examining a population of healthy young men[51] measured a mean antisaccade latency (± SD) of 270 ± 39 ms, similar to the 262 ± 34 ms antisaccade latency measured in this study. Another large study[52] reported antisaccade latencies of approximately 300 ms, and prosaccade latencies of 236 ms, for 20 year old individuals. The shorter antisaccade latency in our football players may be explained by athletes having shorter latencies than non-athletes.[53] Antisaccade latencies in our study are comparable to healthy athlete controls in other studies.[17,18,54]

Antisaccade latencies are between 27-93 ms greater in concussed individuals compared to healthy participants.[15,17–20,55] Although the participants in this research study were not concussed, they also demonstrated statistically significant increases in saccade latency. Our study predicts an increased latency of 5.2 ms for a football player who accumulates 1000 impacts. Although this difference does not reach the clinically important level, the difference between saccade latencies at baseline from season to season is approaching a MCID. Our determination that each head impact results in an increased saccade latency, regardless of time of season,[56] indicates that there is a cumulative effect of head impacts on brain function. The difference between baseline measures indicates that this effect persists from season to season. This season-long change in brain function has also been measured in other studies of football,[6,7,27,57] rugby,[9] soccer,[58] and hockey.[59] Over a four year varsity career, a football player's saccade latencies could increase 40 ms, similar to reductions in brain activation in senior players compared to freshmen in a football EEG study.[60] That difference in latency is comparable to those seen in a concussed person compared to a healthy control[17,20] and exceeds a MCID level. As these deficits gradually accrue over a long period, the effects may not be noticed by the players. However, it represents an alarming change in brain function. For football players, who have been shown to possess more proficient executive control over their motor systems than non-athletes,[24] a 5.2 ms increase in saccade latency is a 20% added "cost" associated with slower executive control which could dictate success or failure of a play or an increased risk of injury.

In terms of recovery from subconcussive head impacts, boxers who receive more head impacts during a match show 20-40 ms increases in saccade latencies immediately after the match, but return to baseline after 2-3 days of rest.[61] In terms of recovery from concussions, saccade latencies are immediately increased, but are not significantly different between healthy and concussed individuals at 30 days post injury.[17,55,62] Together, these studies indicate it takes 2-3 days of rest for the brain to recover from subconcussive head impacts, and 30 days for the brain to recover from concussion injury. However, our study observed persistent changes in saccade latencies, with an incremental effect of head impacts on saccade latency. Presumably this indicates that players are not receiving enough rest between head impacts to allow the brain to recover. Football players participate in three practices and one game per week, and receive an average of 3-9 head impacts per practice,[28,48,49] and 12-45 impacts per game,[26,28,48,49] depending on their position. As such, the damage incurred by head impacts does not recover before the next practice or game. It appears these frequent head impacts have long-term effects as saccade latencies did not return to baseline nine months later, at the start of the following season.

The 2018 baseline latency EOG measures were longer than the 2017 baseline measures recorded using high-speed video. Both forms of saccade measurement have been validated against gold standards for eye tracking systems[32,63] and with each other,[36,38] reinforcing that this increase in saccade latency represents a measurable difference and not an experimental error.

The days between games and saccade testing varied between participants. Studies have shown that head impacts may cause axonal injury if preceded by another head impact in a short period of time.[64–66] As such, the time between a player's last head impact and their test session was controlled for as a covariate in this analysis. This approach has proven useful for evaluating the relationship between head impact and changes in brain structure.[8]

The current study has some limitations. Over the duration of this study, players from a single team were monitored. Different coaching schemes[67] or practice schedules[68] influence head impact exposures, so the results of this study may not represent other Canadian youth, university, or professional football teams. Additionally, the team underwent coaching staff changes during the study period, therefore experiencing different coaching schemes and practice schedules. A trigger threshold of 15 *g* was used to prevent recording accelerations from normal activities[69], which is consistent with best practices.[25] This 15 *g* threshold decreased the number of head impacts compared to the 10 *g* recording threshold used in other studies[7,27,48,68,70] as it omitted a large number of impacts between 10 and 15 *g*.

The accumulation of head impacts increases football players' saccade latencies. This latency increase is persistent over two successive seasons. These results emphasize the effects of repetitive head impacts on brain function. Risk of long-term brain sequelae increases steadily every 1000 head impacts a player experiences.[71] Head impacts should be reduced during the football season through initiatives at the league level as well as team levels with the coaching staff.[72,73] Players' brains need time to recover from repetitive head impacts not only in the offseason, but also during the season. It is important to examine athletes on an individual basis, as each has their own baseline starting point and recovery trajectory.[74] Future work should look at career head impact exposure and brain function, as well as examining meaningful recovery times between football sessions, such as extending time between games and practices, and reducing the number of contact practices.

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Chapter 4

4 Career Head Impact Exposure Profile of Canadian University Football Players

A version of this manuscript has been submitted to the Journal of Applied Biomechanics for publication.

4.1 Introduction

Research on concussions in sport has been increasing since the new millennium. Establishing a definition, objective diagnosis, and threshold for injury are all topics at the forefront of this research.[1–3] While evidence indicates that concussions cause chemical and physical changes within the brain,[3,4] the precise link between head impact parameters, such as the magnitude and number, and concussion is not yet known. Accordingly, further investigation into the magnitude and number of head impacts, or head exposure, is warranted.

American football is an optimal environment to observe concussive head impacts due to advances in head impact sensors and the high frequency of contact between players.[5–9] Many studies have attempted to determine an impact threshold for concussions, but a definitive injury threshold has not been established and likely does not exist.[1,10–12] Nevertheless, it is clear that the number and severity of head impacts present risks for head injury.[10,13] Studies have measured head impact exposure.[13–15] These studies highlight the importance of considering head impact exposure on a subject-specific basis rather than estimating head impact exposure from aggregate data.

Football head impact exposure is influenced by the rules of the game and league policies.[16,17] There are several rule differences between Canadian and American football that may influence head impact rate and severity. Three major distinctions are the field size (CAN=110 x 65yds, US=100 x 53yds), the number of attempts to achieve a first down (CAN=3, US=4), and the number of players in play per team (CAN=12, US=11). Some evidence from American football indicate that limiting the number of head impacts in practice[18–22] and rule changes to the game, such as changing the kickoff,[17] can affect head impact rates. The larger field size in Canadian football may result in the ball carrier experiencing increased head accelerations during tackles due to a potential larger closing distance between the tackler and ball carrier.[23] The fewer number of downs and more players on the field can influence offensive play selection; typically, the Canadian game involves more passing plays. A run-style offensive scheme was associated with more head impacts than a pass-style scheme, and the pass-style scheme was associated with higher magnitude head accelerations.[24] Additionally, the fewer number of downs results in more special teams plays, where more severe impacts occur than on offensive or defensive plays.[23] Accordingly, it is important to evaluate the magnitude and frequency of head impacts in Canadian football as American data cannot be generalized to the Canadian game and there is a paucity of head impact data in Canadian football.[25–27]

One effective injury reduction measure is limiting the number of head impacts that players experience. Growing evidence indicates that repetitive head impacts have a deleterious effect on the brain.[28–31] These repetitive head impacts do not present with clinically visible symptoms or outward signs of neurological dysfunction, but show physical changes to brain structures.[28–31] Systematic reviews of subconcussive impact studies indicate that exposure to repetitive head impacts increases the risk of microstructural and functional changes to the brain.[8,32] These reviews conclude that head impact exposure should be minimized for all athletes.

Several studies have quantified a single season of head impact exposure in football players,[13,26,33–36] and a handful of studies have quantified head impact exposure in multiple seasons.[37–39] One study predicted lifetime head impact exposure from players' estimated length of time playing football.[14] A more accurate depiction of a football player's career head impact exposure is required to establish an athlete's injury risk and any correlations to long-term health outcomes. This includes considering positional differences[15,26,37–39] and their career length. Specifically, it is important to evaluate how a player's head impact exposure changes with seniority on a team, as cumulative head impacts reduce brain activation in upper year players compared to first year players.[40] Rather than estimating exposure, or extrapolating from a single season of collected head impacts, collecting head impact data over multiple seasons would provide definitive head impact exposure data.

With the apparent rule differences between the American and Canadian football game and the lack of longitudinal prospective measurement of head impact exposure, the purpose of this study was to quantify head impact exposures for Canadian university football players over their varsity career. We hypothesized that players' number of career head impacts would be proportional to their number of athletic exposures, freshmen players will have more impacts in a season than senior players within each positional group, that head impact exposure will differ amongst positional groups, and mean head impact magnitudes will increase with seniority across positions.

4.2 Methods

4.2.1 Participants

Western University football team members who participated in training camp, practices and games for a minimum of three seasons between the Fall 2013 and 2018 USports (Canadian intercollegiate) football seasons were eligible to participate in this study. Western University's Health Sciences Research Ethics Board approved the protocol and all participants provided informed consent. Out of 102 football players who were members of the varsity football team for a minimum of three seasons, 63 players were included in this longitudinal study. These players represented a variety of football positions (Table 4.1). Data were available for all players in their junior year, but fewer players in other playing years based on coaching decisions and number of available devices (Table 4.2).

Table 4.1. Demographics of Career Canadian Varsity Football Players for Each Position[a]

Position	**Number of Players**	**Mass, mean (SD), kg**	**Height, mean (SD), cm**	**Age, mean (SD), years**
Defensive Back	12	84.63 (4.95)	181.40 (3.50)	23.08 (1.04)
Linebacker	8	93.95 (4.66)	181.61 (4.07)	23.01 (1.46)
Defensive Line	9	117.53 (15.52)	190.78 (4.66)	23.40 (0.96)
Offensive Line	11	134.18 (12.94)	193.04 (5.90)	23.03 (1.18)
Quarterback	4	92.08 (7.15)	186.69 (4.86)	23.27 (1.23)
Running back	10	94.44 (10.75)	182.12 (4.64)	23.26 (0.71)
Wide Receiver	9	88.30 (5.64)	185.14 (6.53)	22.92 (1.00)
All Positions	**63**	**101.72 (20.41)**	**185.78 (6.59)**	**23.13 (1.04)**

[a] Body mass, height and age are from final season of play.

Table 4.2. Number of Canadian Varsity Football Players in Different Positions for Each Successive Year of Seniority[a]

Position	Freshmen	Sophomore	Junior	Senior	Fifth Year
Defensive Back	3	6	12	11	9
Linebacker	2	6	8	7	4
Defensive Line	0	5	9	9	6
Offensive Line	2	8	11	10	8
Quarterback	1	4	4	4	1
Running back	2	8	10	9	8
Wide Receiver	0	6	9	9	6
All Positions	**10**	**43**	**63**	**59**	**42**

[a]All players participated in at least three seasons, and are counted in this table for each year of seniority they participated.

4.2.2 Instrumentation

The GForce Tracker version 2 (GFT2, Artaflex Inc., Markham, ON, Canada) was used for data collected in 2013, and GForce Tracker version 3 (GFT3) was used for data collected since 2013. Both models contain a tri-axial accelerometer and gyroscope, a lithium ion rechargeable battery, and on-board storage for storing from 400 (GFT2) to 10,000 (GFT3) impacts. The accelerometer has a range of ± 200 *g* and a 1 *g* resolution on each axis, and the gyroscope measures rotational velocities with a range of ± 2000°/s and a 1°/s resolution on each axis. The GFT triggered and recorded data when any of the three linear accelerometers measured an acceleration greater than the user-defined threshold; this study used a threshold of 15 *g*, which is consistent with best practices defined in a recent review.[41] The device recorded data for a 40 ms window for each impact, including 8 ms preceding the threshold. Each impact was time stamped and recorded to the onboard storage. One device was adhered to the inside of each participant's helmet, right of the crown cushion, using an industrial strength recloseable fastener (3M^{TM} Dual Lock^{TM} Recloseable Fastener SJ3551 400 Black, St. Paul, MN). These locations and mounting are similar to previous studies[27,42–45] and have been validated against measures recorded at the centre of mass of the head using a Hybrid III anthropometric test dummy headform.[42] Helmets were inflated to pressures according to manufacturer's recommendations and fitted by the team's equipment manager.

4.2.3 Data Collection Protocol

A record of participant attendance and activity schedule was documented for each practice; impacts that did not occur in a practice drill were discarded. The GFT data were transferred to a laptop after each practice and then uploaded to GForce Tracker's cloud-based storage. A summary file describing every impact (time stamp, peak linear acceleration, peak angular velocity, and helmet location), and the linear acceleration and angular velocity time series data, were exported after each practice.

Participant attendance was recorded at every game. A custom LabVIEW program (version 2010, National Instruments, Austin, TX, USA) recorded which participants were on the field for each play of the game. These data were later used to ensure that only impacts occurring to participants competing on the field were included for analysis. As with the practices, data were downloaded following each game.

4.2.4 Data Reduction

Data reduction focused on the peak linear acceleration and peak angular velocity for each head impact. Similar to previous research,[42] the peak resultant linear acceleration and peak resultant rotational velocity at the centre of mass of the head were estimated using an impact location correction algorithm based on location dependent equations.

4.2.5 Statistical Analysis

All statistical analyses were completed using R.[46] Descriptive statistics for number of impacts, linear acceleration and rotational velocity are reported as mean and standard deviation. A correlation was performed to examine the linear relationship between the number of head impacts in a career and the number of athletic exposures. A correlation coefficient value of 0.3 to 0.5 was considered fair, 0.6 to 0.8 moderately strong, and greater than 0.8 a very strong relationship.[47] An athletic exposure was defined as a practice or game in which the player participated in full equipment (did not have to receive a head impact).[48]

The career head impacts were evaluated using a linear mixed effects model evaluating the contribution of player position and seniority as fixed effects. The number of athletic exposures was controlled as a covariate in the model, as players participated in different numbers of games and practices. As these data were collected over six seasons, with varying combination of players, opponents and overall success of the team, the season played and individual differences were modeled as random effects. To determine the model-of-best-fit for the head impact data, four separate models (null hypothesis, position effects only, seniority effects only, and seniority by position interactions) were tested. The null model consisted of the total number of head impacts predicted by the covariate of type of athletic exposure (game and practice) and random effects. The position and seniority models tested these factors as fixed effects, and the interaction model added the intersection of position and seniority to the prediction equation. In evaluating the goodness-of-fit among the models, the position and seniority models were compared with the null model. In contrast, the interaction model was compared with a model in which position and seniority were included without interacting. Differences among levels of the fixed effect were tested using t-tests, and evaluated with a Satterthwaite approximation of the degrees of freedom.[49]

To test if linear acceleration and rotational velocity magnitudes increased with a player's seniority within each position, similar linear mixed-effect analyses were performed. Both linear accelerations and rotational velocities were compared using an interaction of position and seniority as fixed effects. Session (game or practice), season, and player were random effects. Our null model was determined by main effects of position and seniority with the same random effects. The interaction model was again compared with a model in which position and seniority were allowed to predict number of head impacts without interacting.

Mixed effects models were evaluated using the lme4[50], lmerTest[51], and car[52] packages. Treatment contrasts were used to compare each level of fixed effect to the reference level. Tukey post-hoc analyses compared differences between positions using the emmeans[53] package. Experiment-wise alpha was held to 0.05 within all families of comparisons.

4.3 Results

A total of 127,192 head impacts were recorded over six seasons from the 63 players. The mean number of impacts in a career across all positions was 2023.1 (SD = 1296.4). Players averaged 37.1 (20.3) impacts/game and 7.4 (4.4) impacts/practice.

The number of possible athletic exposures varied in each season, ranging from 37-45 practices and 10-12 games, depending on the success of the team. The number of head impacts varied between positional groupings (Figure 4.1).

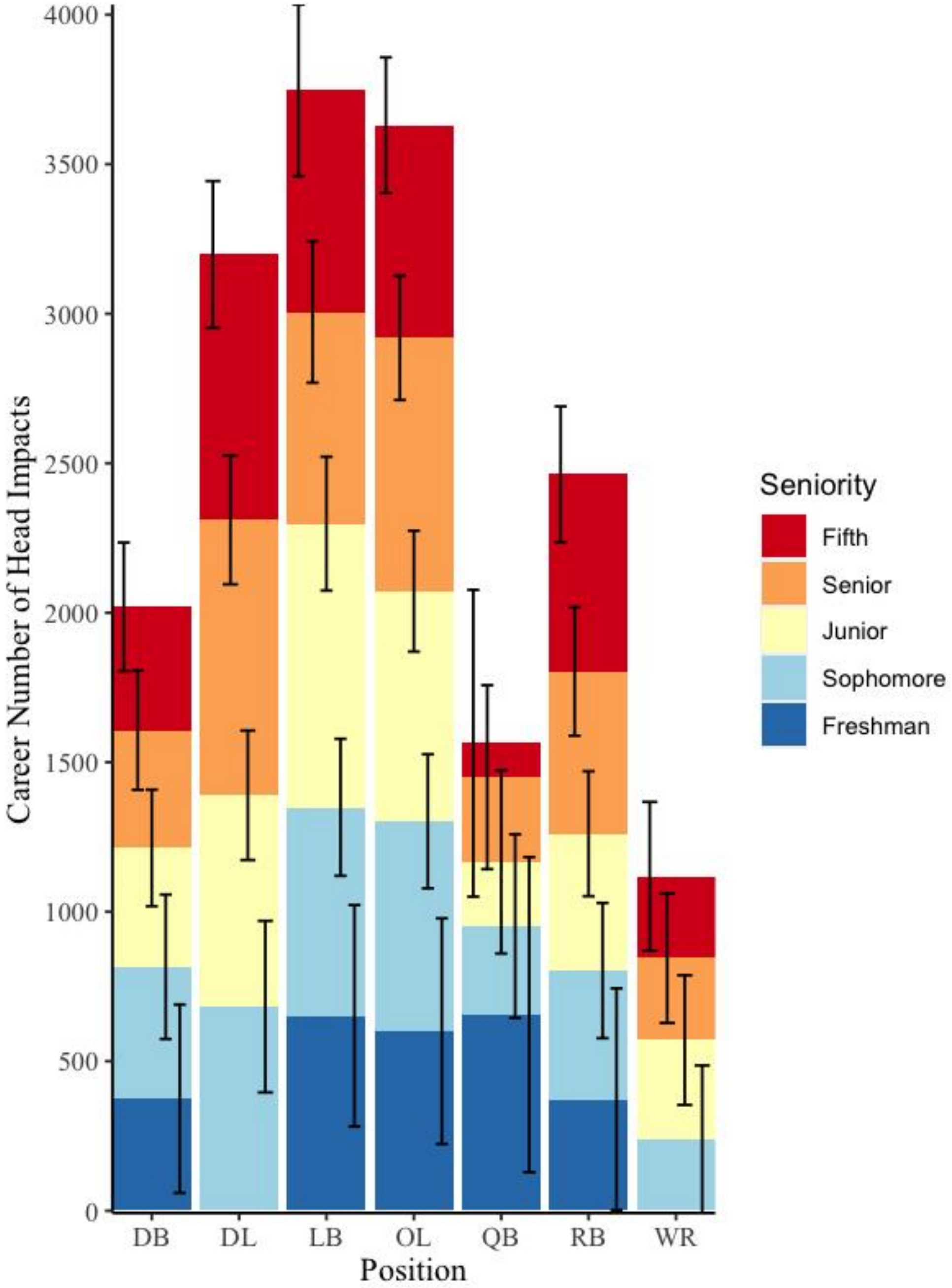

Figure 4.1. Average number of head impacts experienced by a Canadian varsity football player each year of seniority across all positions. Black vertical error bars indicate 95% confidence intervals for each year of seniority. DB = Defensive back; DL = Defensive lineman; LB = Linebacker; OL = Offensive lineman; QB = Quarterback; RB = Runningback; WR = Wide Receiver.

There was a fair to moderate strength positive association between the total number of head impacts in a career and the total number of athlete exposures ($r = 0.57$). On average, players accumulated 23.2 head impacts per athletic exposure (95% CI 14.7-31.6, $t_{61} = 5.38$, $p < .001$, Figure 4.2).

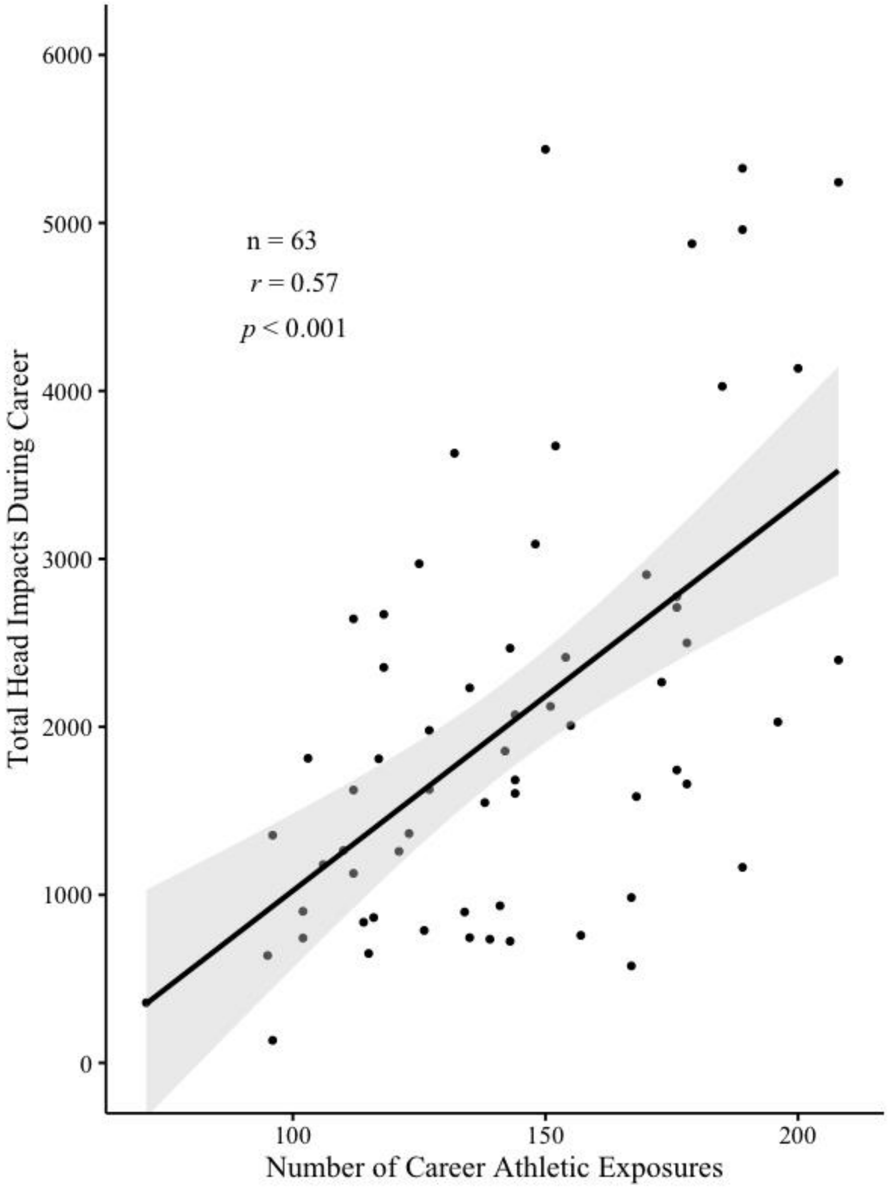

Figure 4.2. The relationship between the total number of head impacts experienced by Canadian varsity football players during their career and their total number of career athletic exposures. Shaded area represents 95% confidence interval. An athletic exposure was defined as a game or practice in which a player participated in full equipment.[48]

The number of head impacts that players experienced in a season differed significantly between different player positions $\left(\chi^2_6 = 39.25, p < .001\right)$. Defensive linemen experienced more head impacts than defensive backs ($t_{62} = 4.03$, $p = .003$), quarterbacks ($t_{59} = 3.90$, $p = .004$), and wide receivers ($t_{62} = 4.83$, $p < .001$). Linebackers experienced more head impacts than defensive backs ($t_{62} = 3.51$, $p = .01$), quarterbacks ($t_{59} = 3.52$, $p = .01$), and wide receivers ($t_{61} = 4.35$, $p = .001$). Offensive linemen experienced more head impacts than defensive backs ($t_{55} = 3.63$, $p = .01$), quarterbacks ($t_{55} = 3.56$, $p = .01$), and wide receivers ($t_{55} = 4.50$, $p < .001$, Figure 4.3).

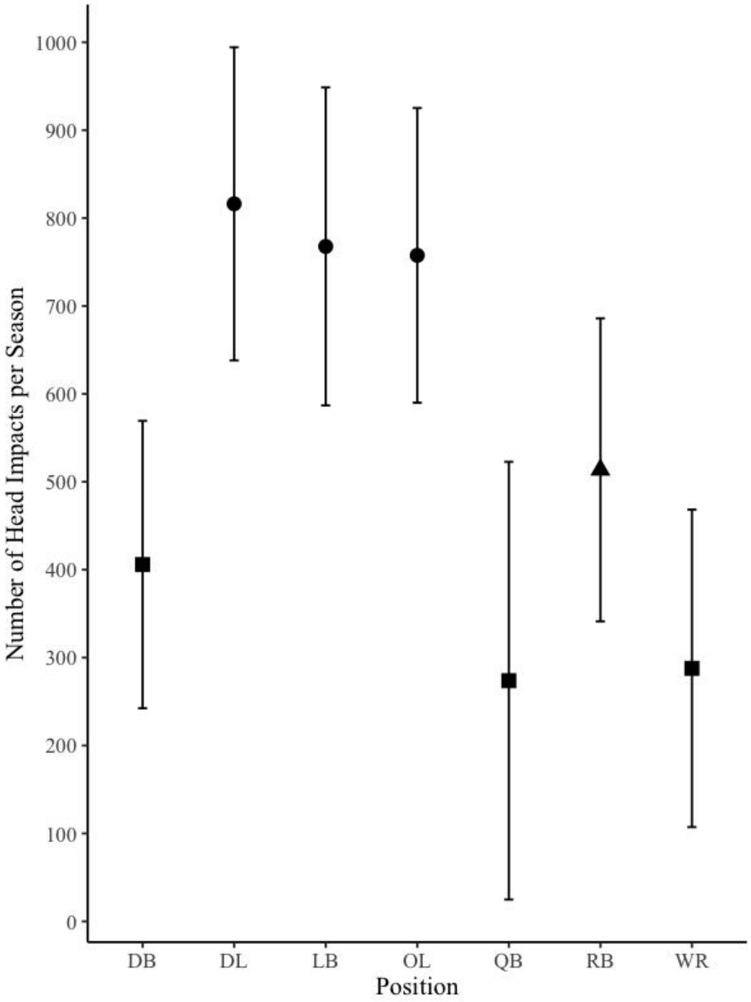

Figure 4.3. Number of head impacts experienced by a Canadian varsity football player in a season by position. Bars indicate 95% confidence intervals. DB = Defensive back; DL = Defensive lineman; LB = Linebacker; OL = Offensive lineman; QB = Quarterback; RB = Runningback; WR = Wide Receiver. Positions indicated with a circle experienced significantly more head impacts per season than positions indicated with a square. Positions indicated with a triangle were not significantly different than any other positions.

Seniority had no statistically significant effect on the number of head impacts that a player experienced ($\chi^2_4 = 2.70$, $p = .61$, Figure 4.4) and the interaction between position and seniority had no statistically significant effect on the number of head impacts that a player experienced ($\chi^2_{21} = 26.78$, $p = .22$, Figure 4.1).

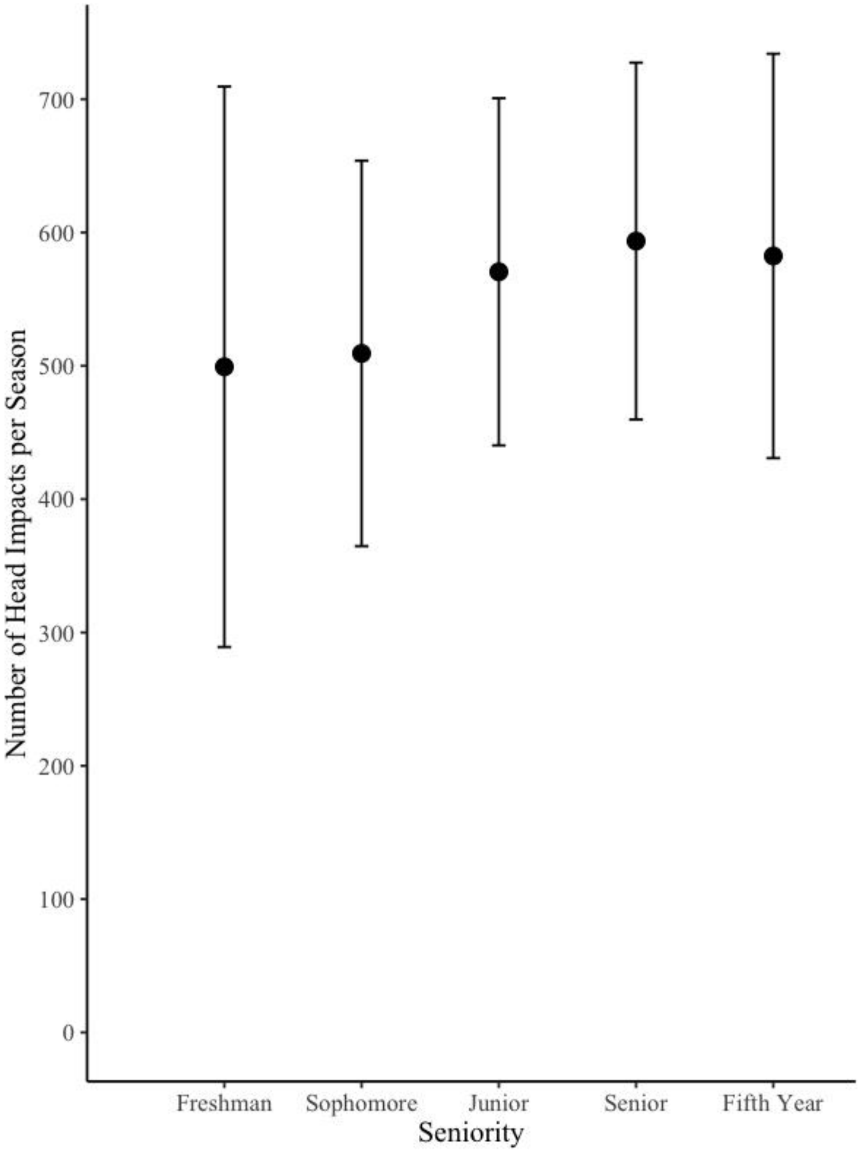

Figure 4.4. Number of head impacts experienced by a Canadian varsity football player in a season by seniority. Bars indicate 95% confidence intervals.

Considering the magnitude of the head impact accelerations, the mixed effect model revealed a statistically significant interaction between position and seniority on linear head acceleration, ($\chi^2_{23} = 526.43$, $p < .001$, Figure 4.5). Linear acceleration increased with seniority within each position for most player positions. As exceptions, senior defensive linemen and quarterbacks experienced greater linear acceleration magnitudes than their fifth year counterparts. As well, junior linebackers experienced greater linear acceleration magnitudes than their senior and fifth year counterparts, and sophomore running backs greater than junior running backs.

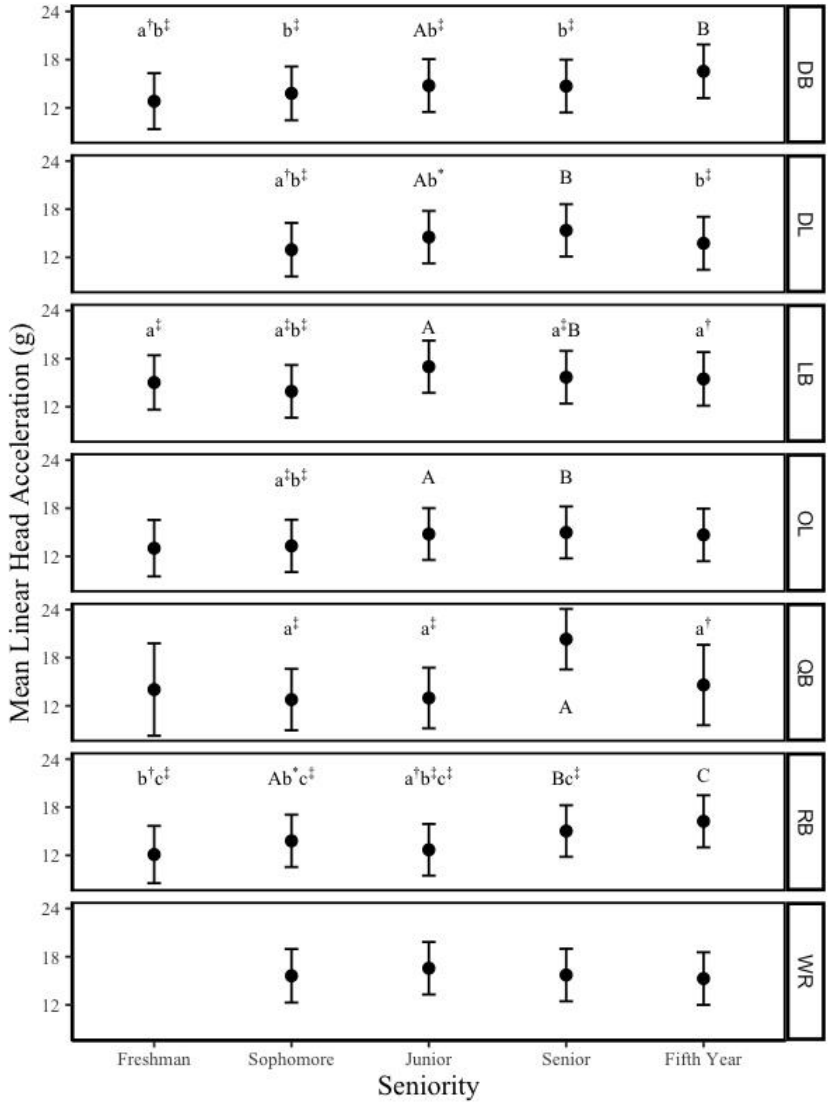

Figure 4.5. Mean linear head acceleration experienced by Canadian varsity football players by seniority across seven positions. Bars indicate 95% confidence intervals. DB = Defensive back; DL = Defensive lineman; LB = Linebacker; OL = Offensive lineman; QB = Quarterback; RB = Runningback; WR = Wide Receiver. An uppercase letter indicates a statistically significant larger mean linear head acceleration than the corresponding lowercase letter, within the same position. * p-value < .05, † p-value ≤ .01, ‡ p-value ≤ .001.

Considering the peak magnitude of the head impact rotational velocities, the mixed effect model revealed a statistically significant interaction between position and seniority, ($\chi^2_{23} = 350.81$, $p < .001$, Figure 4.6). Rotational velocity magnitudes increased with seniority within each position for most player positions. As exceptions, freshmen linebackers experienced greater rotational velocity magnitudes than sophomores, and junior linebackers greater than seniors and fifth year players. As well, senior quarterbacks experienced greater rotational velocity magnitudes than their fifth year counterparts.

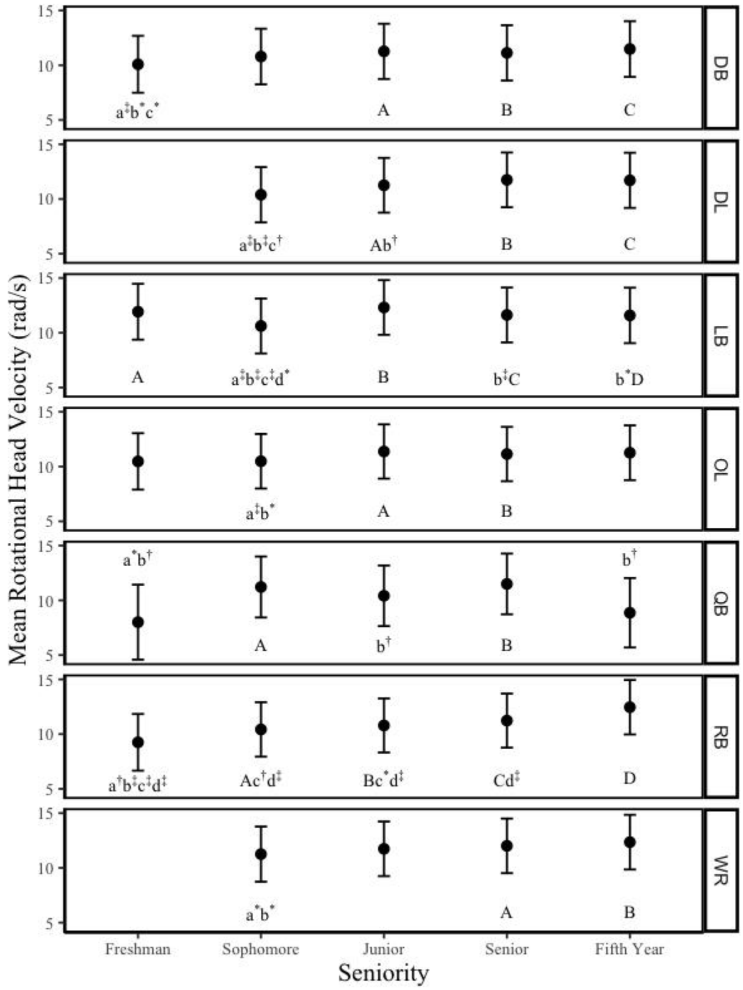

Figure 4.6. Mean rotational head velocity experienced by a Canadian varsity football player by seniority across seven positions. Bars indicate 95% confidence intervals. DB = defensive back; DL = Defensive lineman; LB = Linebacker; OL = Offensive lineman; QB = Quarterback; RB = Runningback; WR = Wide Receiver. An uppercase letter indicates a statistically significant larger mean rotational head velocity than the corresponding lowercase letter, within the same position. * *p*-value < .05, † *p*-value ≤ .01, ‡ *p*-value ≤ .001.

4.4 Discussion

The purpose of this study was to quantify head impact exposures for Canadian university football players over their varsity career. Examination of data from players that participated in three or more seasons revealed that players' number of head impacts were proportional to their number of athletic exposures. Additionally, linebackers and linemen experienced more head impacts than defensive backs, quarterbacks, and wide receivers. In contrast with our hypothesis, seniority did not significantly affect the number of impacts that players experienced; however, it did affect the magnitudes of the mean linear head acceleration and rotational velocity within positional groups.

The current study has several noteworthy limitations. Over the duration of this study, players from a single team were monitored. Teams with different coaching schemes[24] or practice schedules[18,22,54] may experience different head impact exposures, so the results of this study may not represent other Canadian university football teams. As well, the team underwent numerous coaching staff changes during this period and experienced different coaching schemes and practice schedules. Additionally, this study evaluated university players, so these results should not be extrapolated to Canadian youth, high school, or professional levels. The relationship between head impact exposure and player injuries, such as concussion, was not examined in this study. The number of available devices for measuring head impacts varied between seasons (range 47 to 98) which influenced the distribution of the players in the study. The devices were assigned to starting players, as indicated by the coaching staff, to ensure the majority of game impacts were recorded. For example, since most freshmen did not play in games, fewer freshmen were monitored for head impact exposure than other years of seniority; no head impact exposure was available for freshmen defensive linemen and wide receiver positions. This study used a trigger threshold of 15 g to prevent recording accelerations from normal activities[55], which is consistent with best practices.[41] This 15 g threshold decreased the number of head impacts compared to the 10 g recording threshold used by some researchers,[9,18,22,34,35,37,43] and increased the average head impact magnitudes by omitting the large number of impacts between 10 and 15 g.

This study encompassed multiple seasons. Accordingly, athletic exposure was an important factor for all analyses as player participation and the number of practices and games varied each season. In sports, exposure to risk of injury is often reported by the number of athlete exposures.[56] While this concept is valuable for assessing injury risk due to participation, it does not account for specific injury mechanisms. For head injuries, athlete exposures do not capture magnitude or frequency of head impacts. A higher incidence of concussion has been associated with higher frequency of head impacts when weighted using injury risk curves.[57] Therefore, examining the relationship between head impact frequency and athletic exposure was an important element of this study. A previous study examining American college football players found a similar medium strength positive association (r=0.64) between head impacts in a single season and athletic exposures.[36] This relationship is expected as positions vary in the number of impacts per athletic exposure. For example, a quarterback will likely not experience any head impacts in practice, and an offensive lineman may experience more impacts than other positions. Thus, two players with the same athletic exposure will likely experience differing numbers of head impacts. Hence, player position and type of athletic exposure (practice or game) will also contribute to the variance in number of head impacts, and decrease the strength of the relationship between number of head impacts and athletic exposures.

While no studies have examined season impacts across a player’s varsity career, numerous studies have calculated the number of head impacts a college football player experiences in a season.[26,36,37,39,58–61] Similar to these studies, we observed that position was the main factor influencing the number of head impacts a player receives. Specifically, linemen and linebackers experienced greater numbers of head impacts than other positions, which is consistent with other college football studies.[15,25,36,37,59] Both offensive and defensive linemen experience greater numbers of head impacts due to their proximity to the line of scrimmage and starting position of each play in a three point stance (hand on the ground) which encourages their first step to be forward, into their opponent. Linebackers are usually hybrid players on the defensive side of the ball, playing a major role in engaging with offensive players. Accordingly, they are involved in the most plays, while defensive backs or other offensive positions are involved in a smaller number of plays. Linebackers are also involved in most special teams. This likely contributes to linebackers experiencing a greater number of head impacts than other positions. This information may help coaches reduce individual player's head impact exposure. The linemen and linebacker positions would have reduced head impact exposure if some contact drills were replaced with technique-based drills during practices. Furthermore, a recent study[62] determined that linemen in a "down stance" (three or four-point) prior to the snap of the ball were significantly more likely to sustain a head impact in the following play than those in an "up stance" (two-point). Together, these results can help inform coaching practices, and may be useful for defining league policies around lineman stance.

Although seniority was not a significant factor influencing the number of head impacts a player experienced, it still may be an important aspect to consider when evaluating a football player's head impact magnitude. Our initial hypothesis that freshmen players would experience a greater number of head impacts than more senior players was not supported; we did not observe any statistically significant differences in number of impacts with seniority. This is likely because more senior players on this team experience more playing time in games than freshmen. While it would be ideal to account for the time spent in a drill or in a play on the field, it is difficult to implement in these types of studies. Furthermore, upper year players are more likely to receive an increased number of drill repetitions in practices to prepare for game situations. This may relate to previous research observing decreased brain activity in third and fourth year players compared to freshmen, suggesting exposure to head impacts over the course of a varsity career leads to reduced brain activation patterns.[40] The current study indicates an accumulation of head impacts with increasing seniority, which may have subclinical effects on the players' brain function.[28–30] Other studies associated seasons of playing, or age of first exposure, with deleterious effects on the brain and risk of developing chronic traumatic encephalopathy.[63–67]

To the best of our knowledge, ours is the first study to evaluate head impact exposures across years of Canadian university play, including quantifying exposure for different player positions. Linear acceleration and rotational velocity magnitudes increased with seniority within each position for most player positions. Different positions have been compared before and our magnitudes for linear acceleration and rotational velocity are comparable to similar American college football studies.[15,25,26,37–39]

All players in this study increased in body mass from their first season of head impact monitoring to their last. This mass increase could contribute to the increases in linear acceleration and rotational velocity magnitudes seen in this study. Head impact magnitudes have been compared between college and high school players,[58] however the players were aggregated by position only, not by seniority. Collegiate players experienced greater numbers and intensity of head impacts in the highest 1%, 2%, and 5% of impacts compared to high school players. The grouping of high school level players and collegiate level players revealed a difference in head impact magnitudes, so it follows that a more detailed analysis of seniority level would also reveal magnitude differences, as in our study. An important distinction between the American and Canadian football game is the one less attempt to achieve a first down in Canadian football. This rule results in more special teams plays than the American game. Special teams collisions have greater linear and rotational accelerations than offensive and defensive plays.[23] On this specific football team, backup players often compose the special teams to give starters a rest. Backup players are often younger than starters and may play aggressively in an attempt to earn a starting position. This likely contributed to the younger linebackers and running backs experiencing greater impact magnitudes than the more senior players. Only one of the four quarterbacks in this study played to their fifth year of seniority. This player was not the starting quarterback in his fifth year, likely explaining the reduced number of head impacts for fifth year quarterbacks.

Characterizing career metrics of head impact exposure for Canadian university football players is important as they may guide changes to the sport to reduce head impacts. Risk of long-term brain sequelae increases steadily every 1000 head impacts.[68] For the linemen and linebackers in this study, this is nearly a season's worth of impacts. Coaches can consider the number of impacts, and influences of player position and player seniority, to determine ways to reduce head impacts. In particular, changes to practice plans[18,20,54,62] will help to reduce a player's career head impact exposure.

To our knowledge, this is the largest and longest study of head impact exposure in Canadian university football players. We have identified differences in head impact exposure between player positions, that head impact magnitudes differ between positions, and vary with players' seniority throughout their university football career.

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Chapter 5

5 Discussion

This thesis identified football plays that resulted in significant head impact magnitudes between players, investigated the cumulative effect of repetitive head impacts on brain function, and characterized career metrics of head impact exposure for Canadian university football players. This thesis revealed three main findings. Head impacts that occurred during kickoff plays resulted in significantly higher linear and rotational head accelerations than other special teams, offensive, and defensive plays. The accumulation of head impacts significantly increased football players' saccade latencies - effects which persisted over two successive seasons. Finally, seniority did not significantly affect the total number of head impacts that players experienced during their career.

Chapter 2 illustrated that there were no differences in linear and rotational accelerations between striking and struck players when all impact types and locations were considered. This contrasts findings from studies of reconstructed and measured laboratory impacts which resulted in a concussion for the struck player.[1,2] Unfortunately, the laboratory study only evaluated a small number of impacts, which is not indicative of the full spectrum of head impact magnitudes seen in football. The Chapter 2 results also contrast an American college football study that measured greater rotational accelerations in the struck player than the striking player.[3] This difference between the American college football study and Chapter 2 may be explained by the fact that data were collected from both the struck and striking players simultaneously, while the American study only collected data from either the struck or striking players from any given collision. Accordingly, the severity of the collision may not have been comparable between groups of striking and struck players in the American study. The fact that no differences were measured between striking and struck players lead us to believe that there is a similar risk of injury between delivering an impact and receiving one. In conjunction with Chapter 3 results, it is better to simply reduce the number of impacts players receive than to focus on whether they are delivering or receiving impacts.

Therefore, coaches should focus on techniques that keep the head out of the impact, irrespective of impact type (i.e. tackle or block).[4,5]

When impacts were stratified by play type, kickoff plays were identified as having significantly increased linear and rotational head accelerations compared to pass and run plays on either offense or defense. In this thesis, striking players experienced larger linear and rotational accelerations on kickoff cover plays (the kicking team) while struck players experienced larger linear and rotational accelerations on kick return plays (the receiving team). Players on kickoff cover teams are tasked with rushing down the field as fast as possible to tackle the ball carrier. Players on the receiving team are responsible for blocking opposing players from reaching the ball carrier. Accordingly, the measurements from Chapter 2 reflect these football strategies. Linear accelerations for the kickoff were twice as large, and rotational accelerations were three times as large as any other play type. Similar measurements have been made in American college football special teams plays, with higher linear and rotational head accelerations measured in collisions that have larger closing distances.[6] Kickoffs accounted for 6% of all plays, but 21% of concussions in the Ivy League of the National Collegiate Athletic Association.[7] Accordingly, the kickoff has been highlighted as one of the most dangerous plays in American football; which can likely be applied to Canadian football as well. Kickoff rule changes that have been proposed in American football may also reduce head impact severities in Canadian football kickoffs. Such changes include the removal of the onside kick for a fourth down shoot-out style of play, where a team maintains possession of the ball if they are successful in converting for the first down. In the Xtreme Football League, a new American professional football league, the kickoff play is quite different from other leagues. The cover team and receiving team line up facing each other in the receiving team’s half with five yards of space between each other. The kicker remains on the cover team’s 35-yard line to kick the ball. Players from both teams are not allowed to move until the ball is caught by the receiving team. This formation removes the large closing distances that are characteristic of special teams plays,[6] potentially reducing higher magnitude impacts and risk of head injury.

The antisaccade latencies measured in this thesis were comparable to previously published studies of healthy young men[8] and healthy athlete controls.[9–11] Another study reported longer antisaccade latencies (300 ms) for 20 year old individuals, which can be explained by athletes having shorter latencies than non-athletes.[12,13]

The novelty of this thesis has identified a linear relationship between the number of head impacts a football player experiences and neurologic consequences. Taken at first glance, the measured 5.2×10^{-3} ms increase in saccade latency per impact does not seem substantial. However, when combined with cumulative head impacts experienced by football players in a season from Chapter 4, some positions such as offensive linemen and linebackers, who experience 1000-1500 head impacts in a season, will observe 5.2-7.8 ms increases in their saccade latencies from beginning to end of season. The antisaccade task is a measure of executive function.[14] One study established that college football players possess more proficient executive control of their motor systems than non-athlete controls.[15] Specifically, motor impulse control varied by position, and was greater in offensive players than defensive players. In this thesis, prosaccade baseline latencies were approximately 27 ms faster than antisaccade latencies. That 27 ms difference indicates the “cost” of suppressing the voluntary action of looking at the target stimulus and generating a prosaccade in the opposite direction. A 7.8 ms increase in antisaccade latency due to cumulative head impacts in a season indicates a 28% added “cost” associated with the executive control in this situation. In football-related terms, when a quarterback “pump fakes”, or feigns throwing the ball to a wide receiver in an effort to mislead defensive players, linebackers must resist the urge to look at the feigned throw trajectory – they must continue to follow their respective tasks in the play. For a running back and linebacker who both run a 4.4 second 40 yard sprint, a 28% slowing of this reaction time could result in the running back gaining almost 9 yards of space on the linebacker during the “pump fake”, leaving the player wide open. Thus, the measured 5.2×10^{-3} ms increase in saccade latency associated with each head impact can be the difference between success and failure of a play due to slower executive function. Additionally, a slowed recognition of fake plays could place a player in a vulnerable position of increased injury risk.

The measured 10 ms increases in baseline saccade latencies of players that participated in successive seasons indicated that cumulative head impacts have a persistent effect on brain function. Changes in brain function due to a season of football have also been measured in other football studies.[16–25] Over the course of a four year varsity football career, with 10 ms increases per season, a football player’s antisaccade latency could increase 40 ms, the same magnitude of difference between concussed and healthy individuals.[9,10,26–28] The successful implementation of using saccadic eye movements to measure changes in brain function in this study present a less expensive and portable methodology than imaging techniques,[16–25] and more sensitive measure than neurocognitive tests.[29–31] Accordingly, this methodology can be used to monitor the effects of a “hit count” for football players, similar to a pitch count for pitchers in baseball to prevent overuse of their throwing arm. As a player accumulates head impacts, the effects of these head impacts can be monitored and recommendations made to coaching or medical staff to limit the player’s head impact exposure if there are significant deviations from baseline latency measures.

Future studies should continue to use baseline measures to examine potential differences due to repetitive head impacts. This is particularly important for studies involving football players, since athletes have shorter latencies than non-athletes.[12,13] In concussion studies, it is usually necessary to study concussed individuals as a group as baseline measures are often not available. However, each concussion has a unique recovery trajectory,[32] so it is likely it is the same case for recovery from damage due to repetitive head impacts, therefore it should be studied on a case-by-case basis. Future work should also collect saccade latencies over a player’s entire varsity career, and continue to follow them after their career is over.

In sports, exposure to risk of injury is often reported by the number of athlete exposures.[33] However, this is not an accurate quantification of head injury risk in football as number of athlete exposures does not account for magnitude or frequency of head impacts. A higher concussion incidence has been associated with a higher head impact frequency when weighted using injury risk curves.[34] Thus, the moderate positive association between head impacts and athletic exposures measured in Chapter 4 was an important component of the study. As positions vary in the number of head impacts received per athletic exposure, the strength of the relationship between head impacts and athletic exposures would not be a as strong as, say, risk of non-head related injuries and athletic exposures. The $5.2\text{x}10^{-3}$ ms increase in saccade latency for each head impact in

Chapter 3 indicates every impact has an effect on the brain. As impact magnitude and frequency varies between type of athletic exposure as well as position,[4,35,36] reporting head injury risk by impact magnitudes and frequency should be used to accurately depict a football player's head impact exposure.

One of the most effective ways to reduce a football player's injury risk is to limit the number of head impacts they experience. Chapter 4 reported that position was the main factor influencing the number of head impacts a player receives. Offensive and defensive linemen and linebackers experienced more head impacts than other positions, which is consistent with past American college football studies.[30,37–40] A recent study determined that linemen who set up in a "down stance" (one or two hands on the ground while crouching) prior to the snap of the ball were significantly more likely to experience a head impact in the following play than those in an "up stance" (crouching, no hands on the ground).[4] Other American college football studies have reported a 2:1 ratio of impacts experienced during practice to impacts experienced during games.[36,37] The ratio of impacts was closer to 1:1 for this thesis, which is comparable to other Canadian university football studies.[35,39] Thus, while a reduction in number of head impacts experienced in practice may have a larger effect on overall exposure in American college football linemen, a focus on technique such as keeping linemen in an "up stance" may result in an even greater reduction of head impacts in Canadian football linemen.

Although the hypothesis that player seniority influences the number of head impacts experienced was not supported in Chapter 4, linear acceleration and rotational velocity magnitudes increased with seniority within each position for most player positions. Linebackers and running backs were exceptions to this trend, where younger players experienced greater impact magnitudes than more senior players. As noted earlier in this thesis, an important distinction between American and Canadian football is the one less attempt to achieve a first down in Canadian football. This results in more special teams plays in the Canadian game. As identified in Chapter 2, collisions between players on kickoffs (a special teams play) results in double the linear and triple the rotational acceleration magnitudes as other special teams, offensive, or defensive plays. Similar findings have been reported for American special teams plays.[6] The backup players on the football team studied in this thesis often composed the special teams to give starters a rest. Backup players are often younger than starters and may play more aggressively in an attempt to earn a starting position. This may have contributed to the younger linebackers and running backs experiencing greater impact magnitudes than the more senior players, and why such large magnitude of collisions occur as seen in Chapter 2.

The results of this thesis, in tandem with other football studies, can help inform coaching decisions around practice structure and judgments made during the game. One study determined that shortening high-risk drills in practice (based upon impacts experienced per player per minute), could result in a reduction of 1000 impacts in a linemen's football career, and 300 impacts in a non-linemen's career.[41] Furthermore, differentiating between helmet-only, shell, and full-pad practices will help regulate head impact exposure, as the more equipment a player wears increases their number of head impacts experienced in that session.[42] The implementation of a helmetless-tackling drill[5] will reduce the number of head impacts that players experience. For players involved in kickoff plays, such a tackling drill could reduce the number of high magnitude impacts that were measured in Chapter 2. Similarly, coaching technique focused on placing linemen in an "up stance"[4] will also reduce the number of impacts that players experience. The increase in saccade latency with each head impact in Chapter 3 illustrates how such reductions could affect a player's brain function, and the number of impacts experienced in a career in Chapter 4 show how efforts to reduce impacts in practices and games will reduce overall head impact exposure. Finally, monitoring head impact exposure over the course of the season could inform coaching decisions about game rosters. A player who has experienced a greater number of impacts may have impaired executive function, potentially contributing to a mistake on the field that could cause injury or be detrimental to the outcome of the game.

A limitation of this research is that the majority of head impact data was collected from a single team over six seasons of play. During this period, the team underwent coaching staff changes, thereby experiencing different coaching styles and practice structure. As teams with different coaching schemes[43] or practice schedules[41,42,44] may experience different head impact exposures, the results of this study may not represent other Canadian university teams, nor other levels of play. Future studies should instrument players from multiple teams with different styles of coaching and season lengths to fully represent Canadian university football.

The head impact sensors in this research used a trigger threshold of 15 *g* to prevent recording accelerations from normal activities,[45] which is consistent with best practices.[46] This 15 *g* threshold decreased the number of measured head impacts compared to the 10 *g* recording threshold used by some researchers,[16,19,24,40,41,44,47] and increased the average head impact magnitudes, by omitting the large number of impacts between 10 and 15 *g*.

Methodology for collecting saccade latency measurements changed between the two successive seasons of data collection. The first season used high-speed video while the second season used EOG. Both of these forms of saccade measurement have been validated against gold standard eye tracking systems,[48,49] and with each other,[50,51] reinforcing that the measurements from these systems are comparable. EOG measurements involve a more efficient post-collection analysis, so future work should implement EOG methodology at more frequent time points during the season, for example pre-and post-football game, to measure possible acute differences in saccade latency. While minimal, small amounts of head contact do occur in the football offseason during controlled situations. Therefore, saccade measurements should be collected during offseason periods to determine the effects, if any, of these sessions.

The overall objective of this thesis was to investigate the effect of cumulative head impacts on Canadian university football players. This thesis identified football plays that resulted in high magnitude head kinematics, quantified the effect of individual head impacts via saccade latencies, and characterized career head impact exposure for football players. These results provide evidence that head impact exposure needs to be reduced for the health of the players. Coaches and league administrators can use evidence-based research to employ head impact reduction changes to the sport of football and make the game safer for all players.

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