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Cumulative purposeful soccer heading can lead to compensatory changes in brain activity during combined moderate exercise and cognitive load in female youth soccer players

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Abstract

Head trauma that occurs during sporting events is responsible for an increasing number of emergency department visits in Canada and is associated with an increased risk of developing neurodegenerative diseases. While head injury in American football has been extensively studied, it cannot be extrapolated to non-helmeted sports. Approximately 265 million people are actively participating in soccer and many are 18 years of age and younger. Soccer is unique in that players use their head to redirect the ball; however, the effects of cumulative purposeful soccer heading on brain health are unknown. Accordingly, the objective of this thesis was to quantify head impact magnitudes that female youth soccer players sustain during games and evaluate their influence on electrophysiological functioning both at rest and exercise. This was achieved through three research projects that studied female youth soccer players for an entire soccer season and investigated repetitive soccer heading using methodological equipment including, game video analysis, headbands instrumented with wireless microsensors, as well as electroencephalogram (EEG) recordings. Results indicated that the median number of headers experienced during a single game was one, while the maximum is nine, and minimum is zero (Chapter 2). Furthermore, player age is positively associated with an increasing number of purposeful soccer headers, but there is no association between head impact location and game scenario (Chapter 2). Chapter 3 reveals that game scenario and head impact location significantly affect both linear head acceleration and rotational head velocity magnitudes. As an initial attempt to detect neurocognitive change (Chapter 4), EEG recordings revealed a statistically significant increase in EEG power during exercise compared to rest at each EEG frequency band (Alpha1, Alpha2, Beta1, Beta2, Theta). These differences were amplified when cumulative number of headers were considered, but only for Alpha1, Alpha2 and Beta2. In conclusion, this thesis shows cumulative soccer heading experienced by female youth soccer players could lead to neurocognitive changes after one season of soccer. Furthermore, exercise may help to reveal sub-clinical brain changes due to cumulative soccer heading that are not shown at rest. These findings can help guide data-driven approaches to improve player safety in youth soccer.

Keywords

Adolescent, concussion, head impacts, brain injury, repetitive, girls, sports, prevention, coaching, football.

Summary for Lay Audience

While there are numerous personal and societal benefits from participation in sport, head injuries are a healthcare concern that are responsible for an increasing number of emergency department visits. More recently, evidence highlights that repetitive head impacts experienced through sport may be responsible for the onset of long-term cognitive deficits including Alzheimer's Disease and Chronic Traumatic Encephalopathy (CTE). Considerable research has evaluated American football, while females and adolescents are understudied; even though females have a higher rate of head injury compared to males, and adolescents report more prolonged symptomology. In soccer, players experience repetitive head impacts through purposeful soccer heading; however, their cumulative effects are unknown. Determining the relationship between purposeful soccer heading and brain function can help inform evidence-based interventions to improve player safety. Accordingly, this thesis seeks to delineate the relationship between repetitive head impacts and brain health by evaluating purposeful soccer heading in female youth soccer players. Game video was recorded during an entire season of soccer, and players wore headbands containing microsensors to quantify head impact accelerations. Purposeful headers were characterized by head impact location (front, top, side), player position (defense, midfield, forward) and game scenario (corner kick, throw in, goal kick etc.). In addition, measures of brain activity were collected using electroencephalogram (EEG) recordings to determine changes in brain function, related to cumulative purposeful soccer heading. The findings from this thesis indicate that female youth soccer players frequently head the ball during soccer games, and increasing player age is associated with an increasing number of headers experienced. In addition, the head impact accelerations that result from purposeful soccer heading depend on game scenario as well as head impact location. Lastly, our EEG measures indicate that brain activity increases compared to rest during combined exercise and cognitive load, and that an increasing number of cumulative headers amplifies this difference. These results provide important information to help develop evidence-based criteria to reduce the risk of head injury that results from repeated head impacts, and could improve the safety of players in the short- and long-term.

Co-Authorship Statement

This thesis contains material from three published manuscripts (Chapter two, Chapter three, Chapter four) that encompass the collaborative work of researchers and co-authors. Alexandra Harriss is the primary author of all of the chapters contained in this thesis. She identified and researched this topic, designed studies, as well as collected, analyzed, and drafted each of the manuscripts prior to publication. Chapters two, three, and four were co-authored by Dr. James P. Dickey (Professor in the School of Kinesiology, Faculty of Health Science, Western Ontario), Dr. David M. Walton (Associate Professor in the School of Physical Therapy, Faculty of Health Science), and Dr. Andrew M. Johnson (Associate Professor in the School of Health Studies, Faculty of Health Science). These co-authors contributed to the research design and findings, as well as reviewed and revised manuscripts prior to publication. Lastly, Dr. James WG. Thompson co-authored Chapter four (Evoke Neuroscience Inc, New York, NY, USA). He contributed to the research design and findings and analysis of Chapter 4 as well as reviewed and edited the final manuscript prior to publication.

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Table of Contents

List of Tables

List of Figures

Chapter 1

1 Introduction

Mild-traumatic brain injury (mTBI), which includes sport-related concussion, is common among athletes where up to 3.8 million mTBI injuries related to sport and recreational activities occur each year.[1,2] Head injury in sport has led to an increasing number of emergency department visits in Canada[3,4] and across the globe.[1] Furthermore, emerging evidence has identified that sports related head injury is associated with an increased risk of developing neurodegenerative diseases including, chronic traumatic encephalopathy (CTE)[5] and Alzheimer's disease.[6] These health conditions result in a substantial health and financial burden to individuals, families and communities, and incurs significant economic costs to healthcare.[7]

The most recent international consensus statement on sport-related concussion defines concussion as a traumatic brain injury that is caused by biomechanical forces.[8] The brain's pathophysiological response to concussion has been described previously in animal models.[9,10] Following concussion injury, neurological sequalae can include neuronal depolarization, release of excitatory neurotransmitters, ionic shifts, altered glucose metabolism and cerebral blood flow as well as impaired axonal function.[11,12] One of the hallmarks of concussion injury is that the neurological signs and symptoms associated with injury occur in the absence of macroscopic neuronal damage.[11] Furthermore, concussions are a difficult injury to diagnose, evaluate, and manage as there is no single clinical or diagnostic test to reliably and immediately identify them. Clinically, the immediate signs and symptoms of concussion can include confusion, memory disturbance, dizziness, headache, nausea and visual disturbance.[13] While most players recover within seven to ten days following concussion, concussion-related symptoms may last for weeks, months or even persist in some cases.[14,15] These injuries are particularly worrisome since sport-related concussions may be associated with second-impact syndrome as well as progressive neurodegenerative diseases later in life.[16]

Currently, the majority of concussion research has evaluated American football, but such findings cannot be extrapolated to non-helmeted sports, nor to vulnerable populations. Several experts advocate for research into sports related head injury, with specific emphasis on vulnerable populations such as, youths and female athletes.[17] This is especially important since sport participation is encouraged in an effort to improve physical health, and also enhance psychological and social health outcomes. Current clinical evidence demonstrates that youths and females are at a greater risk of sports related head trauma including concussion and prolonged recovery compared to adult males.[18–21] An 11-year prospective study in high school sports reveals that female soccer has the highest concussion rate among female sports, and the second highest overall concussion rate (0.35 per 1000 athletic exposures) after American football.[18] Furthermore, concussions represent a greater proportion of total injuries in female athletes, where almost 16% of total sport-related injuries are concussions, while only up to 11% of total sport-related injuries are concussions for males.[20–22] Nevertheless, there is still limited data from youth and female populations.

The human brain is a complex system. From birth to early adulthood, the developing brain undergoes rapid changes in neuronal synapses, myelination,[23] and metabolism.[24,25] While adolescents may indeed have greater capacity for neuroplasticity,[26] the developing brain has distinct immaturities[27] and may be more vulnerable to head injury.[23] For example, significant changes in neuronal synapses occur in the developing brain, and certain brain regions develop at different times.[28] The degree of myelination differs, in that the amount of myelin increases throughout the brain in later years of development. Rodent models demonstrate that the pathologies of concussion between myelinated and unmyelinated fibers are different.[23] Damage to unmyelinated axons may influence the degree of morbidity associated with head injury and myelination may provide protection against head injury. Consequently, the less myelinated immature brain of youth athletes may be more vulnerable to head injury. In addition, youth athletes have an immature musculoskeletal system, which may influence head injury. For example, cervical strength as well as head and neck size can influence the magnitude of peak linear and rotational head accelerations.[29] Compared to adults, youth athletes have less-developed cervical musculature. Accordingly, youth athletes may not be as effective at transferring energy that is directed at the head throughout the rest of their body, and ultimately increasing their risk for head injury.[12] Collectively, such differences in brain and musculoskeletal development between youth and adulthood suggest that the developing brain responds differently to head injury and may be more vulnerable.

Many researchers investigating head injury in sport conclude that females have a higher incidence rate of concussion compared to males[30] as well as have more neurological deficits and delayed symptom resolution.[31,32] A recent study on children and adolescent concussion-related emergency department visits or physician visits revealed a 5.5 fold increase in concussion rates from 2003 to 2013.[30] The authors concluded that females had the greatest increase in concussion rates (6.3-fold increase) compared to males (3.6-fold increase). Clearly, there is a need to understand heady injury in such populations.

Approximately 4% of the world's population (265 million people) are actively playing soccer worldwide and many of these players are 18 years of age and younger.[33] Internationally, soccer is one of the fastest growing sports for youths and females; and while it is associated with various health benefits including improved cardiovascular fitness,[34] there is risk of head injury, including concussion.[35,36] For example, concussion is the second most common injury reported in soccer, representing 24% of all injuries sustained.[37] The incidence of soccer related concussions range between 0.22 to 1.2 concussions per 1000 athletic exposures,[18,21,22,38] and the rate of concussions increases with increasing player age.[39] Furthermore, soccer is unique in that players are actively encouraged to use their head to redirect the ball, a technique referred to as purposeful soccer heading.[20] Purposeful heading in soccer is an integral part of the game, it is a complex skill, requiring players to develop the ability to judge the trajectory of the ball and coordinate their body movements accordingly. Purposeful soccer heading presents an opportunity to understand head injury in youth and females in what is a naturally occurring environment.

Over the last two decades, concerns have also been raised surrounding the potential short- and long-term neurological complications associated with repetitive head impacts sustained during sports such as American football, ice hockey and soccer. These repetitive head impacts are often referred to as *subconcussion impacts*.[40] While these subconcussion impacts were initially thought to be harmless, since there are no immediate signs and symptoms of brain injury, these impacts lead to neurocognitive impairment over time, even in athletes without a history of concussion.[40] In soccer, players experience subconcussion head impacts through purposeful soccer heading, which accounts for the majority of head impacts that players experience.[41] The number of repetitive head impacts from purposeful soccer heading per playing hour ranges from 1.8 in females to 2.7 in males.[42] Accordingly, a player who heads the ball several times per game (such as a defender or midfielder) could perform more than 1,000 purposeful soccer headers over the course of a 15-year playing career regardless of playing level.

While the threshold for acute symptomatic head injury is unknown, a theoretical threshold of linear acceleration (82g) and rotational acceleration (5900 rad/s^2) is thought to have a 50% probability of causing a concussion.[43] Laboratory studies have quantified both the linear and angular head impact accelerations associated with purposeful soccer heading.[44–46] One laboratory study reveals that player age does not affect head impact accelerations at constant ball velocities, but there is a significant difference in head impact accelerations between males and females.[47] Female soccer players experience larger linear and rotational head impact accelerations (40.9 ± 13.3 g; 3279 ± 1065 rad/s^2) compared to males (27.6 ± 8.5 g, 2219 ± 823 rad/s^2), which may be related to intrinsic factors such as, neck strength. Nevertheless, these impact magnitudes are much lower than the theoretical trauma threshold.[43] However, the neurocognitive consequences that result from purposeful heading in soccer are unknown, but could be associated with dementia in later life.[48]

Currently, there is minimal objective evidence evaluating the frequency and magnitude of head impacts during youth soccer. Self-report methods for quantifying soccer heading frequency are cautioned, as recent evidence demonstrates youth players may overestimate heading exposure by up to 51%.[49] In addition, data collected from youth soccer scrimmages[50] and weekend soccer tournaments[51] reveal that purposeful soccer heading leads to linear head impact accelerations up to 62.9 g. Head impact magnitudes recorded using sensors positioned in helmets reveal no specific concussion threshold, but can be used to predict the likelihood of concussion.[52] Such technology may prove useful to quantify and evaluate cumulative head impact burden in youth soccer. Still, the majority of studies that measure on-field head impact accelerations are in collegiate athletes, [41,53–56] and may not be generalizable to youth populations. For example, one study demonstrates that the largest head impact accelerations female collegiate soccer players experience during games occurs from goal kicks and drop kicks.[55] Yet, such data has not been measured during youth soccer games. While one laboratory study suggests player age does not influence the resulting head impact magnitudes from purposeful soccer heading;[47] such conclusions may be different in varying sporting environments such as practices and games. Other investigations in American football have quantified head impact characteristics; concluding that player position and impact location are significant factors in accounting for differences in head impact magnitudes.[57,58] Objective evaluations of head impact magnitudes such as player position, game scenario, and head impact location would prove useful in youth soccer age groups to help limit cumulative head impact burden.

Currently, there is no consensus on whether the cumulative effect of purposeful soccer heading leads to neurocognitive changes. This may be due to differences in methodologies, confounding variables, populations, outcome measures, and neuropsychological testing. Studies reveal no differences in neurocognitive testing performance or symptomology between low-, moderate-, and high-exposure header groups,[59] as well as no differences in neuropsychological testing performance,[60] following a 15-minute heading session. Other research has also observed no association between repetitive soccer heading and decreases in neurocognitive functioning.[45–49] Conversely, other emerging evidence reveals that repetitive soccer heading is associated with altered brain neurochemistry,[66] biochemical markers of brain tissue damage[67] as well as structural changes in the brain.[68–70] Short-term effects of purposeful soccer heading are also highlighted in reduced postural control,[71] headache[72] and near point convergence.[73] Nevertheless, due to inconsistent findings, there is no consensus on whether repetitive soccer heading should be banned from youth soccer.[74,75]

The United States Soccer Federation eliminated purposeful soccer heading in players under ten years of age and limited heading to only practices in players aged 11 to 13.[76] If heading restrictions and limitations are implemented in youth soccer, decisions need to be data-driven that are based on youth soccer players. To determine whether exposing youths to repetitive head impacts can result in short- and long-term harm and accelerate neurodegenerative diseases, we need to characterize head impact exposures experienced by youth players and use reliable measures to assess neurocognitive changes. If we are able to identify that purposeful soccer heading is a modifiable risk factor of brain injury, this could help reduce the rate of developing neurodegenerative diseases in the future, leading to improved public health in the long-term.

Considerable effort has been devoted to advanced neuroimaging techniques and serum blood markers, to identify diagnosis and prognosis of sports related head trauma.[77–81] However, the associated costs, invasiveness, limited access to equipment as well as potential risk of harm due to small doses of radiation, reduce their clinical utility.[82] Low risk, non-invasive tests of brain function such as electroencephalogram (EEG) offer critical advantages over other imaging techniques to understand repetitive head impact exposures including, purposeful soccer heading. EEG recordings measure brain activity, and is cost effective, portable, and accessible to the public and healthcare teams. This technique positions surface electrodes on the scalp to record the electrical activity generated by the underlying brain structures.[83] In specific, EEG records synaptic excitation of the dendrites of pyramidal neurons in the cerebral cortex.[84] EEG captures brain waves that are categorized into frequency bands including Theta (4.0–7.9 Hz), Alpha1 (8.0–9.9 Hz), Alpha2 (10.0–12.9 Hz), Beta1 (13.0–17.9 Hz), and Beta2 (18.0–29.9 Hz).[85,86] Unlike imaging modalities such as fMRI and PET, EEG provides high temporal resolution.[84] Accordingly, complex patterns of neuronal activity can be recorded immediately following stimulus administration.[83] EEG is widely used to study the brain organization of cognitive processes such as perception, memory, and attention.[83] The non-invasive procedure can be applied repeatedly to healthy individuals as well as patient populations with no risk or harm.

In mTBI research, EEG recordings can successfully evaluate the degree of head injury,[87–91] and detect subtle abnormalities in brain neurons and networks, even in asymptomatic athletes.[92] For instance, spectral EEG recordings reveal abnormal brain functioning in people diagnosed with a concussion that had otherwise cleared clinical testing measures, such as the Immediate Post-Concussion Assessment and Cognitive Test (ImPACT).[93] Individuals that have normal clinical testing scores with abnormal EEG findings may be exhibiting some type of compensatory brain mechanism. The cumulative effects of repetitive soccer heading may show similar EEG findings, in that participants can successfully perform a neurocognitive task, but only by engaging additional brain resources to compensate for the inability to produce the necessary power. A continuous performance task (CPT) requires patients to respond to target stimuli or refrain from responding to non-target stimuli. The omission and commission errors obtained during CPTs provide valuable information regarding inattention and impulsivity, respectively.[94] It is expected that brain activity abnormalities will become amplified when the task requires additional effort, such as moderate exercise. This approach reflects the clinical experience that exercise can exacerbate concussive symptoms,[8,95] and may highlight neurophysiologic changes compared to resting conditions. Moderate exercise combined with EEG data collection has been successfully used to monitor the brain activity in healthy individuals.[96,97] It is not known whether cumulative head impacts affect how the brain responds to increases in physiological stress combined with cognitive load, similar to that seen in concussion.

1.1 Overall Purpose

The overall objective of this thesis is to delineate the relationship between repetitive head impacts experienced during female youth soccer games and their influence on electrophysiological functioning both at rest and under physiological stress (exercise). This was achieved through three research projects involving female youth soccer players for an entire soccer season and investigated repetitive soccer heading using methodological equipment including, game video analysis, headbands instrumented with biomechanical sensors, as well as electroencephalogram (EEG) recordings.

1.2 Chapter 2 Purpose

To describe head impacts from players on three competitive female youth soccer age groups and compare the number of headers that players perform based on player age, position, and impact location.

1.3 Chapter 3 Purpose

To quantify the linear and angular head impact accelerations that result from purposeful heading during female youth soccer games, and whether the magnitude of head impact accelerations differ depending on the game-scenario and head impact location.

1.4 Chapter 4 Purpose

To explore the relationship between cumulative purposeful soccer heading and electrophysiological brain functioning during a single season of female youth soccer.

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Chapter 2

2 The number of purposeful headers female youth soccer players experience during games depends on player age but not player position

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2.1 Introduction

Purposeful soccer heading can account for up to 90% of the head impacts that players sustain during soccer games.[1,2] Recent work indicates that purposeful soccer heading does not appear to cause concussions in high school soccer players;[3,4] however, repetitive heading exposure may lead to subsequent neurological disorders over time.[5] Nevertheless, methodological short comings make findings inconclusive. For example, one group describes a dose-relationship response between years of professional soccer participation and risk of developing amyotrophic lateral sclerosis (ALS).[6] However, this study recruited a small number of participants and no follow-up studies confirm a causal link.

Neuroimaging studies show that repetitive sub-concussive head impacts may be associated with abnormal changes in white matter integrity. For instance, soccer players without a history of concussion demonstrated increases in radial and axial diffusivity in areas of the brain such as the inferior frontal gyrus, compared to swimmers.[7] This study, however, did not quantify heading frequency in their sample, and while comparisons can be made between the control swimmers group, we cannot conclude whether purposeful soccer heading is responsible for these neural alterations. Other neuroimaging work reveals increased heading exposure is associated with abnormal white matter microstructure and poor memory scores in amateur soccer players.[8] This study only recruited 39 amateur soccer players, with no control group for comparison. Furthermore, recent work in male soccer players shows alterations in neurophysiological and neuropsychological indices of cognitive function.[9] Still, heading exposures were estimated retrospectively by players, and therefore may not accurately represent true heading exposures.[10] The possible effects of heading are even more concerning for youth soccer players,[11,12] as their brains are still developing[13] and may be more vulnerable to the possible neurological effects of repetitive heading.

To fully explore the potential association between purposeful heading and brain health, it is necessary to evaluate the head impacts (type, direction, number) that players incur over an entire soccer season rather than a single game or practice. While heading behavior of collegiate players has previously been measured throughout entire soccer seasons, [2,14,15] youth purposeful heading behavior has not been extensively studied. Accordingly, there is a critical knowledge gap regarding this vulnerable population. Among collegiate soccer players, the number of headers that players perform during a game varies between positions.[2,15] As well, collegiate players perform, on average, a greater number of headers than high school players.[14] These data do not exist for youth age groups. Similarly, purposeful heading behaviors may vary between different age groups but this potentially important moderator has yet to be empirically explored.

Furthermore, the quality of heading impact[16] and impulse arising as a function of the impact velocity of the ball and head[17] are also expected to have an effect on forces accrued from each individual header. Proper heading technique requires players to engage their neck musculature as well as meeting the ball with the *os frontale* (forehead) rather than the vertex (top of the head).[18] Improper heading technique, such as poor muscle activation, may lead to greater head impact accelerations.[16,19] Moreover, depending on soccer ball velocity, the magnitude of each purposeful header varies based on game scenario such as a throw-in compared to a goal kick. [17] As a result, certain game scenarios combined with improper heading technique could create even larger head impact magnitudes. Therefore, it is important to identify whether heading technique varies across different youth age groups, but also whether heading technique varies based on game scenario. This information could help inform possible rule revisions for heading in youth soccer, and may inform coaching and training in the development of proper heading technique. The purpose of this observational study was to describe purposeful heading from three competitive youth soccer age groups and compare the number of purposeful headers a player performs based on player age, position, and impact location. We hypothesized that there would be differences in head impact location between player age as well as the game scenario such as drop kicks, goal kicks, and throw-ins.

2.2 Methods

2.2.1 Participants

A convenience sample of three elite (Ontario Player Development League – OPDL) female soccer teams from three different youth age groups in the city of Burlington, Ontario, Canada [under-13 (U13); under-14 (U14); and under-15 (U15)] were recruited for this study. Each of the three teams participated in 20 regular season games over a six-month period. Purposeful heading data were captured for each team as well as the opposing team for each match. Each team and their opposition consisted of up to 18 players per team, with 11 players per team participating on the field at a time. This study was part of a larger scale study exploring the associations between header exposure and brain activity, and some preliminary findings have been previously reported.[10] All players and their legal parent guardians provided written informed consent prior to participation. This study protocol was approved by the Health Science Research Ethics Board at the University of Western Ontario.

2.2.2 Protocol

Game video was recorded and analyzed for all regular season games using a Sony Vixia HD camera mounted to a telescoping tower (EVS25, Endzone Video Systems, Sealy, Texas, United States). Each game video was uploaded to a video analysis software program (dba HUDL, Agile Sports Technologies Inc., Lincoln, Nebraska, United States). The game videos for each age group were reviewed using this video software tool. We also used the software tool to identify each purposeful header impact. Headers were classified according to the team, player, player position, head impact location, and game scenario by a single rater using a standardized rubric created for this study. Player positions were defined as: defense, forward, and midfield. Goalies were excluded from header analysis as they did not perform a single purposeful header. Head impact locations were classified as: front, side, top of the head, back and face. In addition, the game scenario for each head impact was classified as: pass, goal kick, drop kick, deflection, corner kick, throw-in and free kick. Scenarios are described in Table 2.1.

Table 2.1. Description of Game Scenario.

Header Context	Description of scenario
Corner Kick	Kick taken from the corner of the field.
Drop Kick	Kick made by goalie by dropping the ball from the hands and kicking it before it touches the ground.
Free Kick	Kick from a stationary ball awarded to one team as a penalty for a foul by the opposition.
Goal Kick	Kick taken from the six-yard box after the ball has gone over the goal line by the attacking team.
Throw In	Player throwing the ball in from the sideline.
Long Range Kick	Ball kicked from the ground into the air during regular game play
Deflection	Ball being deflected off player before header occurred.

2.2.3 Data Analysis

To ensure a single rater was appropriate to review game video, a subset of five soccer games were reviewed separately by a researcher and a trained expert in soccer. The interrater reliability of purposeful header impact identification from game videos was assessed using Cohen's Kappa. The number of purposeful headers that players performed during all games are reported descriptively as median, minimum, and maximum. In addition, purposeful headers for the Burlington U13, U14, and U15 teams were captured for their entire season, therefore we also report the median number of headers that players experience throughout an entire soccer season. Each team and their opponent has 10 players (not including goalies) on the field at a given time. The U13 and U14 players participated in 75-minute soccer games, and U15 players had 90-minute soccer games. Accordingly, incidence rates were calculated as the quotient between purposeful soccer heading exposure and total exposure hours.[20] The incidence of purposeful headers are presented as per 1000 match hours.

To identify predictors of the number of purposeful headers that players performed during games, a linear mixed effects model was used with player age (U13, U14, U15) and player position (midfield, forward, defense) entered as fixed effects. It was expected that some players would be more or less inclined to perform purposeful headers, and also that the number of purposeful headers within each game may be affected by the unique combination of players on the field during that time. Therefore, individual differences and game differences were modelled as random effects. To determine the model-of-best-fit for the purposeful heading data, four separate models (null hypothesis, age effects only, position effects only, and age by position interactions) were tested. The null model consisted of the dependent variable (total number of purposeful headers) predicted only by error (i.e., the random effects), the age and position effects models tested age and position as fixed effects within the analysis, and the interaction model added the intersection of age and position to the prediction equation. In evaluating the goodness-of-fit among the models, the age and position models were compared with the null model, while the interaction model was compared with a model in which age and position were allowed to predict number of purposeful headers without interacting. Differences among levels of the fixed effect were tested using t-tests, evaluated with a Satterthwaite approximation of the degrees of freedom.[21]

A chi-square test was used to assess the statistical significance of the influence of head impact location (front, side, top) and age (U13, U14, U15) on purposeful heading, as well as head impact location and the game scenario where the purposeful header occurred. All statistical analyses were completed using R (R Core Team, 2017), with mixed effects models evaluated using the lme4[22] and lmerTest[23] packages. Experiment-wise alpha was held to 0.05 within all families of comparisons.

2.3 Results

We observed a substantial interrater reliability for the subset of five games that were scored by two researchers (κ=0.76, 95% CI [0.4 to 1.0]). Accordingly, based on this level of reliability,[24] all of the remaining videos were evaluated by a single rater. In total, there were 1,661 purposeful headers captured during the 20-game season. The U13 players performed 404 purposeful headers, U14 players 589 purposeful headers, and U15 players 668 purposeful headers. None of the players experienced a concussion during games that resulted from purposeful heading. The median number of purposeful headers experienced for the entire soccer season of the Burlington teams increased with age: U13 median = 6 (range 1 to 42), U14 = 17 (1 to 56), U15 = 23 (4 to 66). The incidence of purposeful heading was 74.04 (95% CI [73.9, 74.6]) purposeful headers per 1000 match hours. For all age groups, the median number of purposeful headers experienced during games was one, and the minimum number of purposeful headers was zero. The maximum number of purposeful headers performed during a single game by a U13 player was eight, and nine for both U14 and U15 players. Age had a statistically significant effect on the number of purposeful headers that a player performs [χ^2 (2) = 10.33, p = 0.006]. U15 players head the ball more during games compared to U14 [t(360) = 2.13, p = 0.034] and U13 [t(146) = 3.15, p = 0.001] players.

Player position had no statistically significant effect on the number of purposeful headers that a player performs [χ^2 (2) = 3.09, p = 0.21], and the interaction between age and position had no statistically significant effect on the number of purposeful headers that a player performed [χ^2 (4) = 5.48, p = 0.24]. The number of purposeful headers that players performed during games based on position and age are reported in Table 2.2.

Table 2.2. Number of headers players performed based on player age and position during a single 90-minute (U15) and 75-minute soccer game (U13, U14).

	U13		U14		U15	
	Median	Range	Median	Range	Median	Range
Midfield	1	0 - 8	1	0 – 7	2	0 – 9
Defense	1	0 - 6	1	0 – 9	2	0 – 8
Forward	1	0 - 7	1	0 - 4	1	0 - 4

No purposeful headers occurred at the back of the head (occipital) or face, therefore were not included in head impact location analysis (Table 2.3). Our results indicated a statistically significant association between head impact location and age [χ^2 (4) = 10.40, p = 0.034] (Table 3). There was no significant association between head impact location and game scenario [χ^2 (12) = 12.02, p = 0.44] (Table 2.4). However, the most frequent purposeful heading scenarios resulted from long-range passes (42.4%) and throw-ins (26.7%).

Table 2.3. Headers characterized by head impact location and age.

	Head Impact Location				
Age	Front	Top	Side	Back	Face
U13	271	124	9	0	0
U14	352	209	28	0	0
U15	439	199	30	0	0

Table 2.4. Headers characterized by head impact location and kicking scenario.

	Head Impact Location			
Game Scenario	Front	Side	Top	Total # of headers
Corner Kick	45	2	17	64
Drop Kick	97	3	52	152
Free Kick	42	3	24	69
Throw In	271	22	151	444
Long Range Kick	453	29	222	704
Goal Kick	42	3	24	69
Deflection	125	8	46	179

2.4 Discussion

Relatively little information is known about the heading behaviors and header burden among different youth age groups. Therefore, the current study followed three competitive youth soccer teams for an entire soccer season to evaluate purposeful heading behaviors. Results from this study indicate that the number of purposeful headers performed by players increases as player age increases. Furthermore, our findings reveal that the U14 players make contact with the ball using the front of their head less frequently than expected, and strike the ball with the top of their head more frequently than expected. In addition, the U13 players make contact with the ball using the side of their head less frequently than expected. However, there is no significant association between head impact location and game scenario.

Youth soccer teams participating in the Ontario Player Development League are limited to a maximum number of training hours per week. Players on the U13 and U14 teams are allowed up to 6 hours of training per week, while U15 age groups are allowed up to 7.5 hours of training per week (excluding games and sport sciences related training). Nevertheless, while the Ontario Player Development league has requirements that players need to be educated through training on increased heading skills, there are no requirements to heading limitations/restrictions. Given our findings reveal that players in all age groups struck the ball with the top of their heads (improper heading) between 30 and 35% of the time, it may be that there should be consideration for improved header training in youth age groups.

Recent guidelines for limiting and restricting soccer heading have been implemented in the United States[25] with the intent of reducing concussion risk. This initiative was created due to the concern that repetitive head impacts could lead to both short- [26] and long term[27,28] neurological impairments. Youth players may be more vulnerable to the potential neurological consequences that result from repetitive head impacts due to ongoing brain development.[29] Consequently, as a precaution, this initiative bans heading for youth players ten years old and younger, while players between 11-13 years old can only perform up to 20 headers per week or 30-minutes of heading drills during practice. Nevertheless, these heading limits are arbitrary. In our study, the maximum number of purposeful headers that each age group performed during games were greater than previous work evaluating head impacts during youth soccer tournaments[1] and female youth soccer scrimmages.[30] These differences may be due to shorter duration of soccer tournaments and scrimmages compared to regular 90-minute season games.

While previous work has associated cumulative heading with changes in white matter microstructure,[8] electrophysiological changes,[9] as well as symptoms associated with concussion,[31] the number of headers experienced by these studies are greater than our sample. The number of purposeful headers is particularly important since transient changes in corticomotor inhibition have been measured following 20 consecutive headers over a ten-minute period;[32] however, these laboratory findings are limited to recreating game situations in controlled/artificial settings, which lack external validity. Furthermore, in our sample youth players experience a smaller number of purposeful headers, over a larger amount of time, during games. Consequently, most laboratory studies may not accurately represent true heading exposures for this age group[19,32] as well as studies that estimate heading exposures from player self-report.[8,33] The long-term impact of whether improper heading technique leads to worse neurological sequalae, compared to proper heading technique is unknown. Our results illuminate realistic heading exposures for these youth age groups and accordingly, may be helpful to inform laboratory studies examining the relationship between heading exposure and potential neurological sequelae. In turn, this will help to develop rules and regulations for youth players based on youth data rather than relying on findings from controlled laboratory studies or extrapolating findings from collegiate player data.

In our study sample, 29-35% of purposeful headers experienced by all age groups were performed with the top of the head. This is concerning because head impact location may lead to greater head impact accelerations. For instance, one study indicated that during female youth soccer scrimmage front and side headers result in greater rotational head accelerations compared to the back of the head.[30] While the authors reported no differences in magnitude of linear or rotational acceleration between the top and front of the head, only 47 headers were captured and compared. Furthermore, heading technique is influenced by both muscle pre-tensing, and head-torso alignment, which can decrease the magnitude of linear accelerations following heading, but is less consistent for reducing rotational acceleration.[16] Finally, there are differences in how these skull accelerations relate to actual brain strains, such that lateral impacts to the head could result in higher shear stress compared to frontal head impacts.[34]

Compared to collegiate female players,[15] our findings demonstrate that youth females experience less headers during their soccer season, even when participating in a greater number of season games. Moreover, in contrast to collegiate players,[2,15] the number of headers that youth players perform do not vary between player positions. In our current study, the majority of purposeful headers resulted from throw-ins and long-range passes, which according to previous work results in lower impact magnitudes compared to goal drop kicks and goal kicks.[17] Future studies should quantify these impacts over an entire youth soccer season using wearable acceleration sensors to quantify head impact exposures.

There are some limitations to our current findings. Firstly, this study only captures heading behaviors for female youth soccer players in the Ontario Player Development League, and therefore we cannot comment on whether other soccer leagues and/or calibers would show similar purposeful heading exposures. Female soccer players have a greater rate of concussion compared to male soccer players;[35] however, heading should be described in male soccer seasons as previous work indicates males head the ball more frequently than females.[1] It is possible male soccer players engage in more aggressive play during games compared to females, contributing to their increased purposeful heading burden. Furthermore, our heading data only includes games and not practices, therefore we cannot comment on any differences in heading behaviors, nor the number of purposeful headers, between games and practices. Also, our study only assessed purposeful headers and did not include unintentional head impacts. Lastly, the low number of headers per game per player was challenging to analyse using inferential statistics.

We believe our results provide important information towards data-driven approaches to help guide decisions regarding heading restrictions in youth soccer. The magnitude of head impact accelerations in youth soccer have been quantified in some youth age groups;[1,30] however, the understanding of the cumulative effects of these subconcussive impacts remains unknown. Therefore, larger-scale, longitudinal studies are needed to help understand whether there is a relationship between the magnitude of these impacts and brain health. Such studies will help inform decisions regarding game scenarios associated with larger head impact accelerations, and drive clinical decisions regarding possible heading thresholds. While youth players experience fewer head impacts than collegiate teams, our study shows that purposeful heading in youth soccer is a frequent and expected part of the game that requires further investigation.

2.5 Conclusion

The current study captured purposeful headers from players on three competitive youth age groups as well as their opposition, and compared the number of purposeful headers that a player performs based on player age, position, impact location, and game scenario. We observed that the number of purposeful headers that youth players perform increases as player age increases; however, proper heading technique, as judged by head impact location, is not influenced by player age. Furthermore, head impact location is not influenced based on the game scenario. Although youth players experience fewer purposeful headers during games, as well as entire soccer seasons, compared to collegiate players, purposeful heading is a frequent part of youth soccer.

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Chapter 3

3 Head Impact magnitudes that occur from purposeful soccer heading depend on game scenario and head impact location

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3.1 Introduction

The potential for long-term neurological impairment resulting from repetitive head impacts is a concern for athletes participating in contact and collision sports such as ice hockey, rugby, and American football.[1,2] Emerging evidence also shows neurocognitive effects associated with purposeful soccer heading.[3–6] Observational research has determined that under-14 youth female soccer players can perform up to nine purposeful headers during a single soccer game, and can accumulate more than 50 purposeful headers during a soccer season.[7] While the cumulative linear and rotational head impact accelerations experienced by collegiate players[8] are greater than that of high school players,[9] the developing brains of younger players[10] may be more vulnerable to neurological impairments, even at lower head impact accelerations and cumulative loads.

In 2016 the United States Soccer Federation announced the Recognize to Recover program to limit the number of purposeful headers that youth players perform.[11,12] This initiative bans heading for players younger than ten years old, and limits the number of headers that players aged 11-13 can perform during practices. These thresholds for safe headers were defined through expert consensus rather than empirical evidence, raising questions as to their appropriateness for preventing neurocognitive problems. Other leagues have used data-driven models to reduce the incidence of impacts during sport.[13,14] For example, the number of head impacts that collegiate American football players experience during practices is limited by imposing practices with no equipment, and enforcing that no tackling occurs during these practices.[15] We cannot create empirically-derived guidelines for this vulnerable population without such data for youth soccer.

Several studies have quantified the magnitude of head impact accelerations during soccer games[16–18] though few have fully characterized these head impacts as far as their context is concerned. For example, one study evaluating female collegiate soccer players revealed that purposeful headers occurring from common maneuvers such as “shots” and “clears” result in larger linear head accelerations compared to “passes”;[8] however, it did not report rotational head accelerations that may be a better predictor of neurological consequences of repetitive head impacts.[19] Most such work has been conducted on adult collegiate players,[8,9,16,17,20,21] and youth players have been relatively understudied. [22,23]

Purposeful headers account for the majority of impacts sustained by female youth soccer players during scrimmages, and result in large peak linear and rotational accelerations (4.5 – 62.9 g and 444.8 – 8869.1 rad/s^2, respectively).[24] Other work has quantified youth head impacts during weekend soccer tournaments and report similar impact magnitudes.[22] Youth players have reduced head mass and neck strength, compared to adults, which may lead to larger head accelerations with impact.[25,26] One group revealed that female high school soccer players showed moderate, consistent negative correlations between neck strength (flexion, extension, left lateral flexion, and right lateral flexion) and resultant linear head acceleration in header drills.[27] Other work indicates greater head size and neck strength are associated with lower peak linear and rotational accelerations,[28] while sex and age may not influence head impact accelerations.[29]

Cellular, structural, and metabolic changes,[30] as well as neurocognitive outcome measures such as, verbal learning[31] are also critical components to understanding impairment that results from heading. Although the number of headers alone is unlikely to be enough to fully understand the risk of purposeful heading, the game scenario in which the header occurred may also influence the head impact magnitude. For example, “drop kicks” and “goal kicks” result in significantly larger head accelerations than “kicks”.[18]

Laboratory,[21] and on-field,[23] studies reveal that head impact location influences the magnitude of linear and rotational head accelerations that result from purposeful soccer heading. Accordingly, to fully understand the linear and rotational head accelerations that result from purposeful heading in youth soccer, game scenario and head impact location may provide valuable information for developing informed guidelines in youth soccer.

The purpose of this study was to quantify the linear and angular head kinematics that result from purposeful heading during youth soccer games, and to determine whether the magnitude of these head impacts are influenced by the game scenario and head impact location. Consistent with previous work[18,21,23,32] it is hypothesized that purposeful headers occurring from drop kicks will result in the largest linear head accelerations, and that purposeful headers occurring from corner kicks will result in the largest rotational velocity. Furthermore, we hypothesize that purposeful headers performed with the top of the head will result in larger head accelerations compared to the front or side of the head.

3.2 Material and methods

3.2.1 Participants

This observational study recruited a convenience sample of 36 female soccer players (13.4 (SD 0.9) years old, 1.6 (SD 0.1) m, 50.6 (SD 8.7) kg) from three elite youth soccer teams (U13, U14, U15) participating in the Ontario Player Development League (OPDL). Players competed in one game per week during their soccer season. Players also participated in weekly practices; however, these data were not recorded. Written informed consent from parents and written informed assent from players was obtained prior to participation. This study was approved by the Health Sciences Research Ethics Board at The University of Western Ontario.

3.2.2 Instrumentation

Head impacts for each game were recorded using wireless sensors (GForce Tracker (GFT2), Artaflex Inc., Markham, Ontario, Canada) at the back of the head that were secured with a headband, similarly to other work.[18,27] The GForce Tracker sensors contains a tri-axial accelerometer and a tri-axial gyroscope that measure linear acceleration, and rotational velocity, respectively. The sensors triggered when head impacts exceeded a linear acceleration of 7 g, as preliminary data measured prior to the soccer season indicated that purposeful header impacts can be as low as 8 g. The devices recorded 8 ms of data preceding the threshold and 32 ms of the data following the threshold. Linear accelerations were sampled at 3000 Hz, and filtered through an onboard analog low-pass filter with a cutoff frequency of 300 Hz. Rotational velocity was sampled at 800 Hz, and low pass filtered with a cutoff frequency of 100 Hz. All data were time stamped and stored on the sensors' onboard memory. Although some researchers have incorporated a rigid body kinematic transformation to predict the accelerations at the center of mass of the head,[18,29] we report impact measurements based on sensor data, similarly to some other researchers.[27,33,34] Following each game, head impact data were uploaded to a cloud-based server. Peak linear acceleration, and peak rotational velocity for each head impact were extracted for further analysis.

3.2.3 Study Protocol

A total of 60 regular season games (20 games per team) were recorded using a Sony Vixia HD camera that mounted to a telescoping system (EVS25, Endzone Video Systems, Sealy, Texas, United States). Game video was uploaded to a video analysis software program (dba HUDL, Agile Sports Technologies Inc., Lincoln, Nebraska, United States). An appointed researcher matched each purposeful header from the video with the associated peak linear acceleration and peak rotational velocity collected from the sensor. One rater was deemed appropriate for this analysis based on previous work.[7] The appointed researcher also categorized heading events by game scenario (Table 3.1) as well as head impact location: front, top, back, and side of the head.

Table 3.1. Description of game scenario.

Header Context	Description of game scenario
Corner Kick	A stationary kick taken from the corner of the field after the ball crossed behind the goal line by the defending team
Drop Kick	Kick made by goalie by dropping the ball from the hands and kicking it before it touches the ground. Also called a drop kick by some researchers
Free Kick	Kick from a stationary ball awarded to one team as a penalty for a foul by the opposition
Throw-on	Player throwing the ball in from the sideline
Deflection	Ball was deflected off another player or body location before a header occurred
Pass in Air	Ball was kicked into the air by a player
Shot	Ball was kicked by a player towards the goal by opposing player to score a goal and the defending team headed the ball.

Descriptive statistics for peak linear acceleration and peak rotational velocity are reported as mean and standard deviation. Both linear acceleration and rotational velocity were evaluated using a linear mixed effects model to test whether the game scenario and head impact location predicted head impact magnitude resulting from purposeful heading. Game scenario (pass, shots, free kick, corner, deflection, goal kick, drop kick, throw-in), and head impact location (top, front, side, back) were entered as fixed effects. Individual differences and game differences were modelled as random effects. To determine the model of best fit, four separate models were tested: null hypothesis, game scenario by head impact location interactions, including their main effects. All statistical analyses were carried out using R[35] with linear mixed effects models evaluated using lme4[36] and lmerTest.[37] Effect sizes can be misleading and inaccurate when using linear mixed effect modelling,[36] and are therefore not reported. Statistical significance was defined using a threshold of 0.05.

3.3 Results

A total of 434 purposeful headers were identified from video analysis with matching events recorded with microsensors. Overall, the mean linear head acceleration experienced by players was 18.8 (SD 10.2) g, and the mean rotational velocity was 1039.0 (SD 571.3) °/s. The majority of purposeful headers occurred from passes in the air and throw-ins (Table 3.2). On average, purposeful headers that occurred from shots resulted in the largest linear head acceleration, while corner kicks resulted in the largest rotational velocity (Table 3.2).

Table 3.2. Linear acceleration and rotational velocity resulting from different game scenarios.

Game Scenario	Frequency (%)	Linear Acceleration (g)	Rotational Velocity (°/s)
Pass in air	179 (41%)	19.74 ± 10.86	1098.29 ± 590.95
Throw In	129 (30%)	17.33 ± 6.67	959.22 ± 488.34
Deflection	43 (10%)	12.55 ± 4.02	793.87 ± 521.58
Punt	35 (8%)	20.40 ± 16.14	1021.34 ± 614.82
Shot	20 (5%)	27.35 ± 13.11	1202.30 ± 497.81
Goal Kick	16 (4%)	20.11 ± 6.88	1206.75 ± 765.43
Corner	12 (2%)	22.92 ± 7.21	1447.42 ± 589.80

In terms of head impact location, headers that occurred on the top of the head resulted in the largest linear acceleration and rotational velocity (Table 3.3). Most purposeful headers were performed by players using the front of their head. No purposeful headers occurred using the back of the head, and therefore this header location was not considered in the statistical analyses.

Table 3.3. Linear acceleration and rotational velocity resulting from different head impact locations.

Head Impact Location	Frequency	Linear acceleration (g)	Rotational velocity (°/s)
Front	277	18.35 ± 8.50	951.88 ± 550.52
Top	137	19.69 ± 12.23	1215.44 ± 588.56
Side	20	19.41 ± 14.89	1037.66 ± 469.62
Back	0	n/a	n/a

The mixed effects model evaluating linear acceleration revealed that game scenario had a statistically significant effect on the linear acceleration that resulted from purposeful headers, compared to the null model [χ^2 (6) = 37.97, p = 0.0001]. Headers that occurred from passes in the air resulted in larger linear head accelerations as compared to deflections [t(417.79) = - 3.88, p = 0.0001], and smaller linear head accelerations as compared to shots [t(426.93) = 3.70, p = 0.002]. There were no other statistically significant findings for game scenario. Head impact location did not significantly influence linear head accelerations [χ^2 (2) = 1.81, p = 0.40]. There was a statistically significant interaction between head impact location and game scenario on linear head acceleration, since the interaction model fit the data significantly better than the main effects model [χ^2 (9) = 20.10, p = 0.02]. Drop kicks resulted in significantly larger linear head accelerations when completed with the top of the head compared to the front of the head [t(410.26) = 3.34, p = 0.001].

The mixed effects model evaluating rotational velocity indicated that game scenario had a statistically significant effect on the rotational velocity that resulted from purposeful headers [χ^2 (6) = 20.84, p = 0.002]. Passes in the air resulted in significantly larger rotational head velocities compared to deflections [t(419.58) = 3.20, p = 0.001] and throw-ins [t(425.98) = 2.18, p = 0.03]. Furthermore, the rotational head velocity from purposeful headers varied significantly between head impact locations [χ^2 (2) = 18.15, p = 0.0001]. Purposeful headers that occurred at the top of the head resulted in larger rotational velocities compared to the front of the head [t(429.49) = 4.30, p = 0.0001]. There was no statistically significant difference in rotational velocity between purposeful headers that occurred at the front of the head compared to the side of the head [t(430.35) = 0.54, p = 0.59]. The game scenario did not significantly influence the rotational head velocity for the different head impact locations [interaction not statistically significant: χ^2 (9) = 8.89, p = 0.45].

3.4 Discussion

While the United States Soccer Federation implemented heading guidelines with the intent of reducing youth heading exposure,[11] there is relatively little information about linear and angular heading kinematics for this age group.[22,23,38] Understanding the frequency, magnitude and on-field characteristics of purposeful heading will provide valuable information to soccer federations to develop data-driven models designed to limit youth cumulative heading exposure. We observed that head impact location affected head impact magnitudes; purposeful headers occurring on the top of the head result in larger rotational velocities compared to the front of the head. When considering both game scenario and head impact location, we found that purposeful headers occurring from drop kicks completed with the top of the head had the largest linear head acceleration magnitudes. However, this relationship was not maintained for rotational head velocity where there was no interaction between game scenario and head impact location.

The head impact accelerations experienced by the youth soccer players in our study were comparable to earlier work that quantified purposeful headers during youth soccer scrimmages[23] and games;[22,38] however, these studies did not categorize headers by the soccer game scenario. This component of soccer heading is important as we observed that there were significant differences in impact magnitudes between the various game scenarios. For example, we observed that purposeful headers occurring from deflections result in reduced linear head acceleration and rotational head velocity compared to passes in the air. Such differences in head impact magnitude between the various game scenarios were likely due to varying ball velocities in these situations. For example, controlled laboratory testing has reveal that headers performed with soccer balls projected at 13.4 m/s result in smaller head impact accelerations compared to 22.4 m/s (30.6 ± 6.2 g vs. 50.7 ± 7.7 g, respectively).[24] As well, soccer ball velocity is reduced when the ball bounces from the ground, or off another player (i.e. deflections), which would lead to a smaller head impact acceleration compared to a pass in the air or goal kick.

One research study suggests that limiting purposeful headers from drop kicks and goal kicks could help reduce the cumulative load of heading in female collegiate soccer;[18] however, our findings indicate this strategy may not be effective for youth age groups. Drop kicks and goal kicks occurred infrequently in our study, and therefore do not add substantially to the cumulative heading load experienced by youth players. Passes in the air accounted for the greatest proportion (41%) of purposeful headers performed by youth players, and shots were the only game scenario that resulted in larger head impact acceleration magnitudes. Passing the ball on the ground, rather than in the air could help reduce the number of recorded headers in this study sample by as much as 41%.

Previous work also indicates that repetitive long-range headers, can negatively influence cognitive functions. For example, soccer players who perform a greater number of long-range headers have slower reaction times on pointing tasks compared to players with fewer long-range headers.[39] However, other work shows no negative changes in computerized neurocognitive functioning among both male and female youth soccer players.[40] It is possible that repetitive exposure to specific purposeful headers, such as long-range kicks, may be more likely to impair cognitive functioning in youth soccer players. Accordingly, limiting the number of purposeful headers that youth players perform from long-range passes in the air could reduce their overall heading exposure.

Previous work has identified differences between head impact location and the magnitude of head impact accelerations in female youth soccer players.[23] Our findings demonstrate that purposeful headers performed using the top of the head result in larger rotational velocities compared to the front of the head, while headers performed using the side of the head did not influence rotational head velocity magnitude compared to the front of the head. These results indicate that players should be trained to execute proper heading technique, impacting the ball with the front of their heads, as this reduces the magnitude of the linear head impact accelerations. In contrast, improper heading technique (i.e. headers performed with the top of the head) can result in larger rotational velocities as well as shear forces.[41] These findings support US Soccer's stance that limiting the overall head impact exposure in soccer, rather than only concussive impacts, is an important aspect of policy development and player safety.[12]

There are some limitations to the current study that should to be acknowledged. The impact magnitudes in this paper are based on sensor data rather than predictions for the head center of mass. This study only quantified head impact accelerations for female youth soccer players during soccer games, and not practices. This study provides meaningful data about purposeful heading for a population that is notably absent in head injury literature; however, we cannot make any comparisons between sexes or different soccer leagues/calibers. Recent findings suggest that heading may cause greater head injury in female soccer players compared to males,[42] and accordingly these findings are pertinent to this at-risk population. The data presents both the linear and angular head impact kinematics for different game scenarios and head impact locations, but we do not report head impact exposure per player. A comparison paper presents information on the different game scenarios and head impact location per player for purposeful headers.[43] Our study only quantified impacts that resulted from purposeful headers, and did not consider non-header impacts. Non-header impacts occur infrequently compared to purposeful heading events,[8] and therefore may not substantially contribute to overall head impact exposure. However, unintentional headers may pose a greater risk of CNS symptoms than intentional headers.[44] It is important to recognize that non-header impacts, such as player to player contact, would be a separate focus for rule changes compared to intentional heading.

Our findings show that purposeful heading in female youth soccer is a common activity, that occurs from various game scenarios, but predominately passes in the air and throw-ins. While similar impact magnitudes were recorded from each of the various scenarios, limiting headers from passes in the air could help reduce youth heading exposure by up to 41%. Furthermore, while most headers were performed using the front of the head, players still use the top of their head for almost one-third of purposeful headers. This is a concern because the rotational head velocity was larger for headers performed with the top of the head compared to the front of the head. Coaching strategies should focus on methods for limiting the number of headers that players perform, perhaps by encouraging players to avoid heading passes in the air, but also educate players on heading technique to reduce cumulative heading burden.

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Chapter 4

4 Cumulative soccer heading amplifies the effects of brain activity observed during concurrent moderate exercise and continuous performance task in female youth soccer players

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4.1 Introduction

Most soccer-related head injuries occur from contact with other players; [1] however, soccer players routinely experience head impacts through purposely heading the ball. Purposeful soccer heading occurs when players deliberately use their head to direct the soccer ball. There is concern that cumulative head impacts through purposeful soccer heading may influence neurological functioning. For example, some studies show that repetitive head impacts, such as purposeful soccer heading, do not lead to immediate changes in neuropsychological testing or advanced neuroimaging, [2–4] while other investigations report adverse sequelae. Using diffusion-tensor imaging, one group reported that the number of headers a soccer player performed within the last year was associated with the degree of axonal injury for specific regions of interest.[5] Another study revealed, elite male soccer players show evidence of increased radial and axial diffusivity in areas of the brain including the corpus callosum, over the course of a normal season.[6] Similar neuroimaging findings have also been reported in American football players who experience repetitive head impacts. [7,8] Collectively, these findings indicate that cumulative head impacts may cause impairments in areas of the brain that are not explained by a history of a diagnosed concussion.

Electroencephalogram (EEG) recordings reveal abnormal brain functioning in people diagnosed with a concussion, yet they have normal clinical concussion test scores. [9] Similarly, EEG abnormalities are shown in people diagnosed with a concussion while performing virtual reality balance and spatial tasks. [10] Taken together, these findings suggest that some type of compensatory brain mechanism is occurring to achieve what appears to be normal functioning. A continuous performance test (CPT) presents patients with stimuli that requires them to respond to target stimuli or refrain from responding to non-target stimuli. Omission and commission errors during CPTs provide valuable information regarding inattention and impulsivity, respectively. [11] Omission errors result when the participant fails to respond to target stimuli, whereas commission errors result when the participant responds to non-target stimuli.

The cumulative effects of purposeful soccer heading may demonstrate EEG abnormalities that are currently reported in patients diagnosed with a concussion[9,10] in that participants can successfully perform a CPT by engaging additional brain resources to compensate for the injured brain areas. It is expected that these abnormalities will become amplified with additional effort, such as moderate exercise, [12–14] making neurological deficits more readily identifiable.

Heading is a frequent part of youth soccer, [15] yet this population is understudied. The youth age period is a sensitive time for the developing brain, [16] potentially rendering this group more vulnerable to the negative effects of purposeful heading. Still, it is not known whether purposeful heading can lead to abnormal brain activity during or after a single soccer season. Accordingly, the purpose of this study was to explore the relationship between cumulative purposeful soccer heading and electrophysiological brain functioning during a single season of female youth soccer. We examined female youth soccer players as they have a higher risk of concussion. [17] This study examined a spectral analysis of EEG to determine whether youth female soccer players demonstrate spectral changes in EEG activity at electrode locations Fp1, Fp2, F3, F4, F7, F8, C3, and C4 at rest and during moderate exercise, while participants completed a CPT. Previous studies show increases in brain activity as a result of exercise. [18,19] Accordingly, our hypothesis was that exercise will result in increased EEG activity for each frequency band across all electrode sites compared to rest. In addition, we hypothesized that these differences between rest and exercise would be amplified as players experience a greater number of cumulative purposeful headers.

4.2 Methods

4.2.1 Participants

Twenty-four elite female soccer players from three different youth age groups (under 13, under 14, and under 15) were recruited for this study. All players were part of the Ontario Player Development League, and competed in 20 regular season games during a six-month period. Participants were excluded if they were diagnosed with a concussion during the season or within the previous six months, or if they had a diagnosed learning disability or any neurological or psychiatric disorders. Participant assent and parent consent were obtained prior to participation. This study protocol was approved by the Health Sciences Research Ethics Board at the University of Western Ontario (HSREB# 107948).

4.2.2 Electroencephalogram recordings

In accordance with the International 10-20 system, [20] 22 electrodes were positioned on the participants scalp using a spandex EEG recording cap (Electro-Cap. Eaton, OH, USA: Electro-Cap, International). Nineteen scalp locations were recorded, and all leads used linked ears as reference, and AFz as the ground. Impedances at all recording sites were below10 kΩ. Electroencephalogram recordings were twenty minutes in duration (ten minute resting, ten minute moderate exercise) and completed using the eVox system (Evoke Neuroscience, Inc., New York, NY). The system bandwidth defined by post-processing filters was 1–30 Hz, and the sampling frequency was 250 Hz. Since the antialiasing filter only attenuated the signals to 20% at 60 Hz (Smith 1997), a 60 Hz notch filter was employed to further attenuate any potential signal from power mains.[21] Data were recorded to a Dell Latitude E6440 laptop running an i7 processor.

EEG frequencies were divided into the following bands: Theta (4.0 - 7.9 Hz), Alpha1 (8.0 - 9.9 Hz), Alpha2 (10.0 - 12.9 Hz), Beta1 (13.0 - 17.9 Hz), Beta2 (18.0 - 29.9 Hz).[22,23] Female soccer players frequently experience the majority of purposeful soccer headers on the front and top of the head. [24] Accordingly, we assessed power for each frequency band at electrode sites at the frontal (Fp1 & Fp2), mid-frontal (F3 & F4), lateral-frontal (F7 & F8), and central (C3 & C4) locations as these electrodes are preferentially influenced by neural activity close to these regions, though also affected by neural activity from more distant areas due to volume conduction. Temporal electrode sites were not assessed due to excessive contamination with artifact from masseter muscle activation.

Off-line analysis was performed using Evoke Neuroscience's Report Generator software. Artifact removal and data filtering were specifically tuned for exercise condition, and were used to process the resting conditions as well. Data were manually inspected and segments that contained movement artifacts or excessive muscle activity at any electrode site were eliminated from further analyses. Independent component analysis was used to detect and correct eye blinks in order to improve signal quality.

4.2.3 Experimental Protocol

Video from each of the 20 matches was recorded using a Sony Vixia HD camera mounted to a telescoping tower (EVS25, Endzone Video Systems, Sealy, Texas, United States). The game video was analyzed using a video analysis software tool (dba HUDL, Agile Sports Technologies Inc., Lincoln, Nebraska, United States) and the number of headers was recorded by one researcher for all games. Previous research has determined that one rater is sufficient to reliably record the number of purposeful soccer headers.[15]

Participants avoided caffeine and high intensity physical activity on each of the testing days. EEG testing was conducted at four time points during the soccer season: baseline, two mid-seasons, and a post-season measure. At baseline, anthropometric data and concussion history were collected. Participant EEG were recorded at two conditions, rest and during moderate exercise. During each condition participants completed a CPT, whereby either target (big circle) or non-target (small circle) stimuli were presented on a computer monitor at defined time intervals and the participants responded. The participants were instructed to press a button as quickly as possible when presented with the target stimuli, and refrained from responding to non-target stimuli. Omission errors occurred when the participant failed to respond to target stimuli. Commission errors occurred when the participant responded to non-target stimuli.

For the moderate exercise condition, a cycle ergometer was used to limit movement artifact. [18] Preferred seat height and handle bar position was consistent across sessions. Participants selected a cycling cadence that they could maintain throughout the entire ten minutes. Biking intensity increased each minute throughout the test, based on participant mass and rpm, similarly to other concussion exercise protocols.[25] The Borg rating of perceived exertion (RPE) scale [26] was used at the start and end of the rest and exercise condition. This scale is a simple numeric list and participants verbally reported a number between 6 (no exertion at all) to 20 (maximal exertion) corresponding to their perceived exertion. Participants rested for up to ten minutes between conditions.

4.2.4 Data Analysis

The mean and range are reported for the number of cumulative purposeful headers at each testing time-point. Descriptive statistics for participant demographics and RPE during each condition (rest and exercise) are reported as means and standard deviations. In order to ensure that the effects of sustained exercise were present, we chose to analyze the second half of both the exercise and rest conditions, and treated the initial five minutes as warm-up periods.

Commission and omission errors are reported as median and range as they were not normally distributed. A Wilcoxon signed-rank test was used to determine the statistical significance of the differences in commission errors between rest and exercise. The same analysis was used for omission errors. These analyses were carried out in IBM SPSS Statistics (version 25). A p-value of < 0.05 was considered statistically significant.
The EEG signals were digitized using a separate 24-bit analog-to-digital converter for each channel. Power for Theta, Alpha1, Alpha2, Beta1, and Beta2 were considered as dependent variables. A linear mixed effects model evaluated whether the main effects of testing time, experimental condition (rest, exercise), and electrode site (Fp1, Fp2, F3, F4, F7, F8, C3, C4) predicted EEG power for each dependent variable. Testing time, experimental condition, and electrode site were entered as fixed effects to determine whether the main effects model predicted EEG power for each dependent variable. This main effects model was tested against a null model consisting of only subject variance. Cumulative number of headers was then entered into the main effects model as a random effect, and this revised model was tested against the original main effects model to determine whether or not accounting for this source of error significantly improved the prediction. The interaction (condition by site) was then tested against the main effects model that included cumulative headers. A p-value < 0.05 was considered significant.

4.3 Results

One player sustained a concussion during the soccer season and was excluded from analysis. The mean age of the remaining 23 participants was 13.1 (SD 0.8) years old, with a mass of 49.5 (SD 8.6) kg and height of 1.6 (SD 0.1) m. The average cumulative number of purposeful headers at follow-up was 6.4 (range: 0 - 29), 15.4 (range: 1 - 49), and 23.5 (range: 6 - 61) at follow-ups one, two and post-season, respectively.

4.3.1 Continuous performance test

At each testing session, all players successfully completed the rest and exercise condition. Overall, average RPE difference before (6.55 SD 1.02), and after (6.86 SD 1.75) the rest condition was not statistically significant ($p = 0.34$). During exercise, participants cycled at 57.30 (SD 6.31) rpm. RPE statistically significantly increased throughout the exercise condition (before 6.59 SD 1.30, after 15.7 SD 1.7). Median errors for omission and commission scores are presented in Table 4.1.

Table 4.1. Continuous performance test omission errors and commission errors.

Condition	Outcome measure	Baseline	Follow up 1	Follow up 2	Post Season
Rest (median %, range)	Omission	0.0 (0.0-8.57)	0.0 (0.0-11.43)	2.86 (0.0-11.43)	0.0 (0.0-48.57)
Exercise (median %, range)	Omission	11.43 (0.0-54.29)	11.43 (0.0-34.29)	5.71 (0.0-40.0)	7.41 (0.0-45.71)
Rest (median %, range)	Commission	1.63 (0.0-3.27)	0.41 (0.0-4.49)	0.0 (0.0-3.27)	0.41 (0.0-3.27)
Exercise (median %, range)	Commission	0.82 (0.0-4.90)	0.41 (0.0-7.76)	0.0 (0.0-4.90)	0.41 (0.0-2.04)

There was a statistically significant difference between rest and exercise omission scores, in that omission errors increased during exercise compared to rest at baseline ($z = -3.87$, $p = 0.001$), follow-up 1 ($z = -3.56$, $p = 0.001$), follow-up 2 ($z= -3.10$, $p = 0.002$), and post-season ($z = -2.26$, $p = 0.024$). Conversely, there were no statistically significant differences in rest and exercise commission errors at all testing sessions: baseline ($z = -1.18$, $p = 0.24$), follow-up 1 ($z = -0.13$, $p = 0.90$), follow-up 2 ($z = -0.85$, $p = 0.40$), and post-season ($z = 0.29$, $p = 0.77$). Regardless of experimental condition, all players scored within normal ranges for omission and commission errors, and there was no statistical evidence that cumulative headers influenced the number of omission and commission errors. Therefore, cumulative number of headers were not considered in this analysis.

4.3.2 Alpha1

Considering the Alpha1 frequency band, the main effects model (experimental condition, site, and testing time) were significantly better at predicting EEG power compared to the null hypothesis [χ^2 (11) = 533.94, $p < 0.0001$]. When cumulative headers were entered as a random effect, the main effects model was statistically significantly improved at predicting EEG power [χ^2 (1) = 84.36, $p < 0.0001$]. The interaction model (condition by site) was significantly better at predicting these data compared to the main effects model [χ^2 (7) = 56.09, $p < 0.0001$]. Exercise caused EEG power to increase compared to the rest condition (Figure 4.1). Specifically, a statistically significant difference in EEG power between rest and exercise was demonstrated at the frontal electrode sites (Fp1: 0.15 μV^2 SE 0.02, t(1205)=7.29, $p < 0.0001$; Fp2: 0.14 μV^2, SE 0.02, t(1205)=6.43, $p < 0.0001$; F3: 0.08 μV^2, SE 0.02, t(1205)=3.9, p = 0.0001; F4: 0.07 μV^2, SE 0.02, t(1205)=3.35, p = 0.008; F7: 0.14 μV^2, SE 0.02, t(1205)=6.61, $p < 0.001$; F8: 0.14 μV^2, SE 0.02, t(1205)=6.64, $p < 0.001$). There were no statistically significant differences at central electrode sites (C3: 0.03 μV^2, SE 0.02, t(1205)=1.41, p = 0.16; C4: 0.01 μV^2, SE 0.02, t(1205)=0.35, p = 0.72).

4.3.3 Alpha2

Alpha2 power demonstrated that the main effects model (experimental condition, site, and time) was significantly better at predicting the data than the null model [χ^2 (11) = 461.64, $p < 0.0001$]. When cumulative headers were entered as a random effect, the main effects model was significantly better at predicting EEG power [χ^2 (1) = 29.09, $p < 0.0001$]. The interaction model (condition by site) was significantly better at predicting EEG power than the main effects [χ^2 (7) = 33.81, $p < 0.0001$]. Exercise caused EEG power to increase compared to the rest condition (Figure 4.2). In particular, a statistically significant difference in EEG power between rest and exercise were demonstrated at the frontal sites (Fp1: 0.11 μV^2, SE 0.02, t(1206)=6.37, $p < 0.0001$; Fp2: 0.10 μV^2, SE 0.02, t(1206)=5.86, $p < 0.0001$; F3: 0.08 μV^2, SE 0.02, t(1206)=4.64, $p = 0.0001$; F4: 0.08 μV^2, SE 0.02, t(1206)=4.26, $p < 0.001$; F7: 0.11 μV^2, SE 0.02, t(1206)=6.12, $p < 0.0001$; F8: 0.11 μV^2, SE 0.02, t(1206)=6.07, $p < 0.0001$). There were no statistically significant differences at central electrode sites (C3: 0.04 μV^2, SE 0.02, t(1206)=1.93, $p = 0.05$; C4: 0.01 μV^2, SE 0.02, t(1206)=0.52, $p = 0.60$).

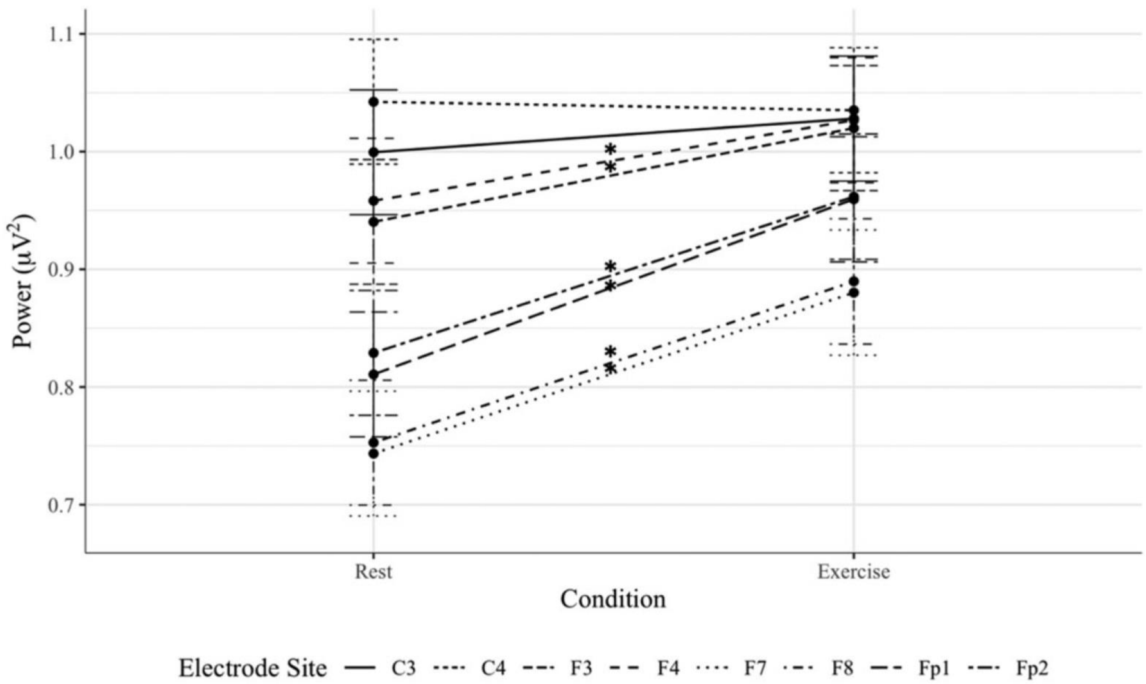

Figure 4.1 Interaction plot illustrating the spectral power in Alpha1 band between electrode site and experiment condition (rest and exercise). The points indicate least square means and error bars represent standard error. Asterisk (*) represents statistically significant differences between rest and exercise ($p < 0.05$).

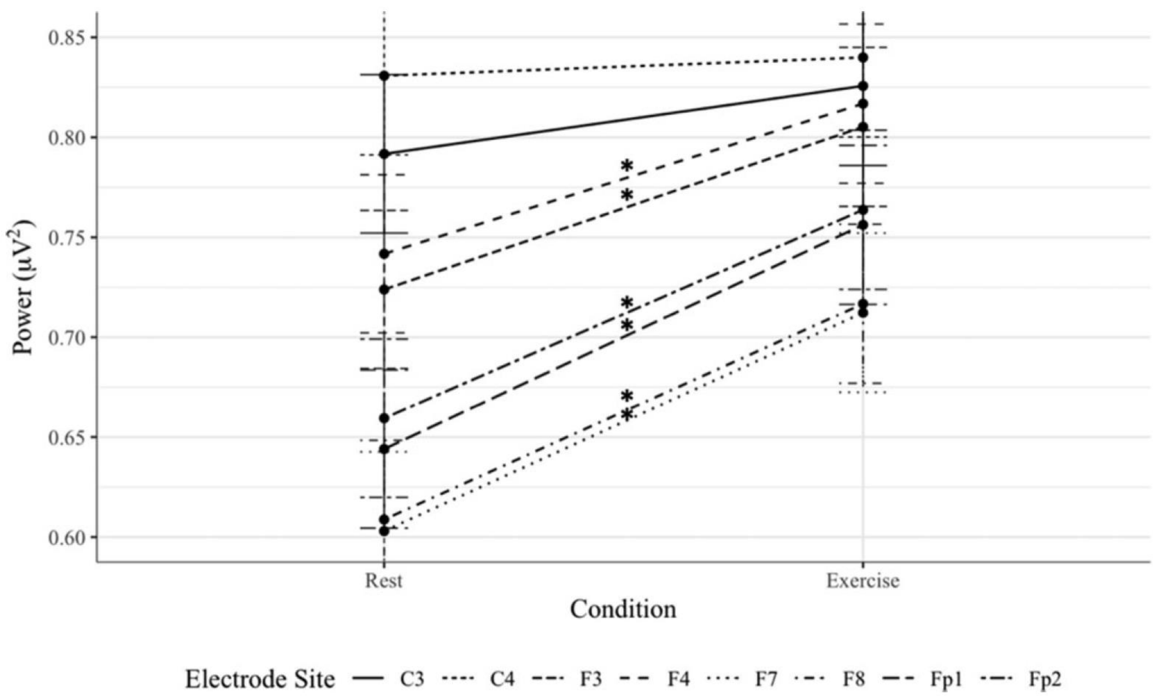

Figure 4.2 Interaction plot illustrating the spectral power in Alpha2 band between electrode site and experiment condition (rest and exercise). The points indicate least square means and error bars represent standard error. Asterisk (*) represents statistically significant differences between rest and exercise ($p < 0.05$).

4.3.4 Beta1

Considering the Beta1 power, the main effects (experimental condition, site, and time) were significantly better at predicting the data than the null hypothesis model [χ^2 (11) = 452.79, $p < 0.0001$]. The main effects model was significantly better at predicting EEG power when cumulative number of headers were entered as a random effect [χ^2 (1) = 68.71, $p < 0.0001$]. The interaction model (condition by site) was not better at predicting EEG power than the main effects [χ^2 (7) = 2.33, $p = 0.93$].

4.3.5 Beta2

Considering the Beta2 power, the main effects (experimental condition, site, and time) were significantly better at predicting the data than the null hypothesis model [χ^2 (11) = 199.25, $p < 0.0001$]. When cumulative headers were entered as a random effect, the main effects model was significantly better at predicting EEG power [χ^2 (1) = 13.10, p < 0.0001]. The interaction model (condition by site) was significantly better at predicting EEG power than the main effects [χ^2 (7) = 20.65, p < 0.004]. Exercise caused EEG power to increase compared to the rest condition (Figure 4.3). A statistically significant difference in EEG power between rest and exercise were demonstrated at electrode sites Fp1 (0.01 μV^2, SE 0.02, t(1209)=1.19, p = 0.004), F3 (0.07 μV^2, SE 0.02, t(1209)=4.20, p < 0.0001), F4 (0.06 μV^2, SE 0.02, t(1209)=3.87, p < 0.001), F8 (0.05 μV^2, SE 0.02, t(1209)=2.89, p = 0.004), C3 (0.08 μV^2, SE 0.02, t(1209)=4.84, p <0.0001), C4 (0.08 μV^2, SE 0.02, t(1209)=4.80, p < 0.0001). There were no statistically significant differences at electrode sites Fp2 (0.01 μV^2, SE 0.02, t(1209)=0.35, p = 0.72), and F7 (0.03 μV^2, SE 0.02, t(1209)=1.67, p = 0.10).

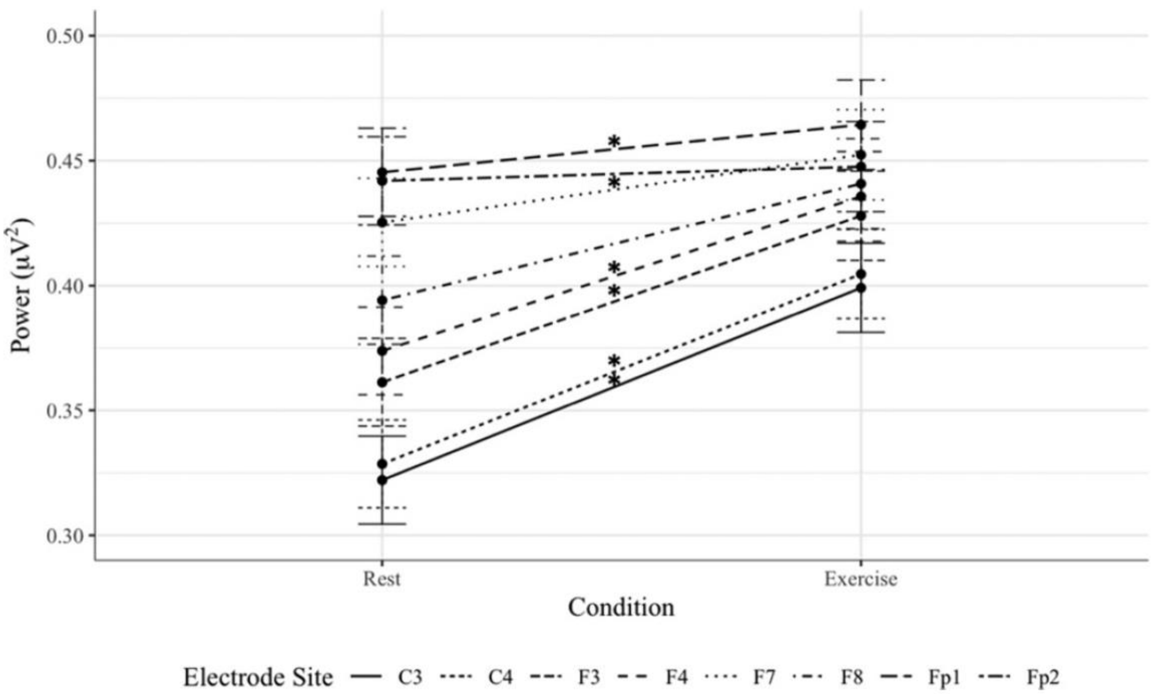

Figure 4.3 Interaction plot illustrating the spectral power in Beta2 band between electrode site and experiment condition (rest and exercise). The points indicate least square means and error bars represent standard error. Asterisk (*) represents statistically significant differences between rest and exercise (p < 0.05).

4.3.6 Theta

The main effects model (experimental condition, site, and time) were statistically significant for Theta power [χ^2 (11) = 508.16, p < 0.0001]. When cumulative number of headers was entered into the model as a random effect, the main effects model was significantly better at predicting EEG power [χ^2 (1) = 130.91, p < 0.0001]. The interaction model (condition by site) did not better predict EEG power than the main effects [χ^2 (7) = 13.77, p = 0.06].

4.4 Discussion

This study evaluated changes in neurophysiological functioning at different times over the course of a female youth soccer season. Consistent with our hypothesis, EEG power during exercise increased at each frequency band compared to rest. As players experienced a greater number of cumulative purposeful headers, these differences in EEG power between conditions were amplified, but only for Alpha1 and Alpha2 power at all electrode locations, but C3 and C4 as well as Beta2 for all electrode locations, but Fp2 and F7.

Similar to previous work, [10] our CPT outcome measures suggest normal functioning, while EEG recordings reveal that the exercise condition had increased Alpha as well as Beta2 power compared to rest. Notably, players that experienced a greater number of cumulative purposeful headers showed a statistically significant increase in Alpha and Beta2 when engaged in moderate exercise. Since the same effect was not seen at rest, these findings suggest that moderate exercise can amplify differences in cortical functioning and may serve as a more sensitive test of impairment in Alpha1, Alpha2 and Beta2 functioning. Although there were statistically significant main effects, none of the interaction models for the remaining frequency bands were better at predicting EEG power. Continuous performance task findings revealed a statistically significant increase in omission errors during exercise compared to rest. This is consistent with previous work, in that error rates increased with exercise intensity [27,28]. We did not observe any statistically significant changes in commission errors between conditions, suggesting no impulsivity or hyperactivity behaviors during the CPT.

Previous work has used exercise to evaluate concussion injury as well as recovery. [12–14] However, we are unaware of any studies that have examined the effects of cumulative header impacts on brain function when measured during moderate exercise. Previous work has shown EEG activity appears to increase during and after exercise in otherwise healthy people. [18] Our findings revealed statistically significant increases in Alpha1, Alpha2 and Beta2 power between rest and exercise. This difference was amplified when cumulative purposeful headers were incorporated into the model as a covariate. The impact of brain injury on alpha power has received much attention due to its possible association with several brain processes, such as its inhibitory control mechanisms. Following mild traumatic brain injury (mTBI), one study showed alpha power suppression during balance tasks pre- and post-mTBI injury. [30] Other work has shown neurophysiological abnormalities in concussed athletes compared to controls including decreased whole brain beta and theta power during EEG baseline testing, as well as reductions in frontal beta power during ImPACT testing that achieved a similar level of performance on clinical tests.[10] These findings suggest that patients with mTBI injuries utilize compensatory neural processes - adaptive strategies and altered brain resources to successfully perform required tasks. It is possible that our findings indicate such compensatory mechanisms.

In collegiate soccer players, there is accumulating evidence indicating a possible association between repetitive head impacts and abnormal changes in neural functioning [31] and structure. [32] However, in youth soccer players, findings from neuropsychological testing batteries have not observed neurocognitive impairment immediately following soccer heading,[3] a weekend soccer tournament, [2] or one month of soccer participation. [33] The lack of findings for neuropsychological testing have been purported to be due to compensatory processes that allow for normal overt behavior function in spite of altered neurological processes. Our findings show that cumulative purposeful soccer heading may be associated with negative changes in neurological function and processes, in female youth soccer players, as indicated by increased alpha power. The novel aspect of this study is that we have demonstrated that measures of EEG power during exercise have the potential to inform researchers and clinicians, such as physiotherapists, of possible cognitive deficits, even at the subclinical level. This information may help provide the opportunity for early intervention remediation for individuals that do not show clinical symptoms.

There are some limitations to our study that should be considered. This study only recorded purposeful soccer headers during games and did not consider practices or non-header impacts (such as head to ground). Purposeful soccer heading has become a health concern, [5] particularly for youth players. [34] In addition, we only evaluated female youth soccer players. Youth male soccer players perform a greater number of headers compared to youth female soccer players during games [35] and practices. [36] Still, female youth soccer players experience a greater number of concussions as well as larger peak linear and rotational header accelerations compared to males. [37] Our study only reported omission and commission errors. We did not report reaction time as it can be challenging when working with special populations. [27] We only reported EEG from anterior sites due to their role in early deployment of cognitive processes, specifically the top-down processes. [38] Recent imaging work also reveals abnormal findings in the anterior region of the brain related to soccer heading such as, frontal temporal atrophy. [32] However, this study did not assess temporal electrode sites such as, T3, T4, T5, T6 due to contamination from masseter muscle activation, particularly during exercise. Accordingly, it is not known whether EEG activity would show meaningful differences in the temporal region, as well as other locations of the brain, such as the posterior region.

While the majority of studies evaluating cumulative soccer heading assessed participants at rest, we explored the effects of cumulative soccer heading during moderate exercise. Omission and commission errors obtained during the CPT reveal that participants at rest are able to achieve normal clinical testing scores; however, increasing task complexity (exercise) reveals statistically significant increases in omission error scores. In addition, EEG recordings show that moderate exercise leads to significant increases in alpha activity compared to rest, and that cumulative number of headers amplified this difference. This suggests that players that experience a greater number of cumulative headers throughout the season produce increased alpha power during exercise. We believe that this increased alpha power reflects a compensatory mechanism in that by engaging additional brain resources, participants can successfully perform a continuous performance test.

4.5 Conclusions

The implications of cumulative soccer heading on brain function in youth soccer players are unknown and understudied. Our findings show that neuropsychological outcome measures (such as omission and commission errors) may show normal cognitive functioning, but that EEG recordings during moderate exercise show sub-clinical neurocognitive dysfunction related to cumulative soccer heading. This study evaluated female youth soccer players for one season of play, and it is not known whether males, or other ages, or duration of study, or soccer calibers, will show similar findings. While omission and commission error scores were within normal clinical scores, measuring EEG recordings during exercise may reveal sub-clinical impairments resulting from cumulative soccer heading.

4.6 References

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Chapter 5

5 Discussion

This thesis characterizes purposeful soccer headers that female youth players experience throughout a season of soccer, and the associated head impact magnitudes. We also investigated whether the cumulative head impact burden experienced by female youth soccer players leads to changes in brain function during combined exercise and cognitive load. The findings of this thesis reveal statistically significant differences in the number of headers performed among the different youth age groups, which were not significantly different between the different player positions. Interestingly, both linear head acceleration and rotational head velocity vary significantly between head impact location as well as game scenario. Finally, players who experience a greater number of headers throughout their soccer season demonstrate increased brain activity for Alpha1, Alpha2, and Beta2 during combined exercise and cognitive load.

The total number of headers that a player experienced during a single soccer game in this thesis was greater compared to youth soccer scrimmages[1] and weekend tournaments.[2] In contrast, another group evaluating heading exposures during soccer games for players between nine and fifteen years of age, revealed that players experience on average 1.64 headers per game.[3] This is greater than the median number of headers recorded in this thesis. The duration of playing time in regular season games is longer compared to playing time in scrimmages and tournaments, which may explain these differences in heading exposures. Furthermore, this thesis identified that player age is related to the number of headers a player performs. This is consistent with previous work in youth soccer, which demonstrates a trend between increasing number of headers and increasing player age.[3,4] Compared to collegiate findings,[5] collegiate players experience a greater number of purposeful soccer headers compared to our study sample. Interestingly, in terms of player position, while mean values for heading exposure indicate that the midfielders head the ball more often in our study sample, these findings were not statistically different compared to the other player positions. These findings were similar to one epidemiological study evaluating youth heading exposures.[3]

The biomechanical sensor data revealed that the mean linear head acceleration and mean rotational head velocity experienced by female youth soccer players is 18.8 (SD 10.2) g, and 1039.0 (SD 571.3)°/s, respectively. The linear head accelerations measured in this study are smaller than linear head accelerations reported in controlled laboratory scenarios. For example, the mean linear head impact accelerations that result from purposeful soccer heading in youth players is 38.5 (SD13.6) g when soccer balls are projected at 11.2 m/s. [6] Another laboratory study demonstrated that soccer balls projected at 13.4 m/s and 22.4 m/s result in head impact accelerations of 30.6 (SD 6.2) g and 50.7 (SD 7.7)g.[7] It is possible laboratory studies do not accurately reflect head impact magnitudes that occur during regular soccer games, as games scenarios and head impact location can result in varying ball velocities.

On field analysis among youth age groups demonstrate comparable head impact magnitudes to our current findings.[1,2] In contrast, one study measuring head impacts over a one-month period reported median linear head accelerations in females of 47.4 g and males of 33.3 g,[4] which are larger compared to the findings reported in this thesis. The variability in head impact magnitudes across these studies may be due to the use of different biomechanical sensors and methodological protocols. For instance, the high triggering threshold for one study[4] (15 g) means that they did not measure lower head impact magnitudes. It is recommended that head impact data should use a 10 g impact threshold,[8] and accordingly the 15 g impact threshold would overestimate mean linear head accelerations. When comparing our biomechanical sensor data to collegiate players, youth athletes experience similar[5] or possibly smaller linear head impact magnitudes.[9,10]

In addition, this thesis identified that purposeful headers from shots result in the largest linear head accelerations, while purposeful headers that occurred from corner kicks result in the largest rotational head velocities. These findings are different compared to collegiate data. For example, larger linear head accelerations and rotational head accelerations occur from goal kicks and drop kicks during collegiate soccer games.[11] Another study indicates that shots and clears result in larger linear head accelerations compared to passes;[10] however, this study did not measure rotational head velocity. Furthermore, our results indicate that all players, regardless of age, will perform incorrect heading technique. This is concerning since improper heading technique (top of the head) was related to greater linear head accelerations and rotational head velocities compared to proper heading technique (front of the head). These findings have also been observed in soccer scrimmages.[1] It is possible that youth soccer players may not be as proficient with judging soccer ball trajectory in the various game scenarios or are unable to coordinate the necessary body movements to successfully head the ball with proper technique. This skill is something coaches can educate players to help them acquire the necessary techniques for tracking the soccer ball in flight and appropriately coordinating their actions.

In healthy individuals, EEG can be used to track the increases in cortical activity that accompany exercise. For example, increases in EEG power are revealed in the frontal regions during high intensity cycling[12] as well as during graded exercise combined with cognitive load.[13] Our EEG findings revealed statistically significant increases in brain activity during combined exercise and cognitive load across all frequency bands. However, when the cumulative number of headers was considered, these differences in brain activity between conditions were further amplified for the Alpha1, Alpha2, and Beta2 frequency bands. The amplification of cortical activity in these frequency bands suggests that a possible compensatory mechanism is occurring to provide the necessary brain power to successfully complete the task.

In asymptomatic patients recovering from concussion, EEG is able to detect residual abnormalities that are not shown at rest.[14] The authors demonstrated that the YMCA Bike protocol significantly increased absolute power for alpha, beta, delta and theta across all brain regions in the asymptomatic concussion group, compared to controls. Nevertheless, EEG findings in concussion are inconsistent across studies. Patients diagnosed with a concussion demonstrate reductions in alpha[15–17] and beta power.[15,18,19] Our study did not identify any statistically significant changes in theta power related to cumulative head impact burden, which is different from concussed individuals. Some research groups indicate changes in theta frequency bands related to concussion injury; however, the outcome measures used and direction of effects are not consistent. For example, relative to baseline or control data, athletes diagnosed with a concussion demonstrate lower theta power,[14,15,20] increased theta coherence[18] and increased frontotemporal theta power.[21] Still, electroencephalogram findings that evaluate the consequences of repetitive head impacts as well as concussion vary. These differences are possibly explained due to different research methodologies, populations, outcome measures, and testing paradigms.

Limitations on purposeful soccer heading were implemented by the US Soccer Federation.[22] This legislation bans heading for youth players 10 years of age and younger, while players 11 and 12 years of age may engage in a limited number of headers per week. Currently, there is little scientific evidence that supports the age-specific guidelines imposed by the US Soccer Federation. Prevention strategies in other sports such as American football, have successfully implemented data-driven guidelines to limit head impact exposure and risk. For example, reducing tackling by regulation of practice equipment worn by American football players reduces the number and magnitude of repetitive head impacts players experience.[23] For soccer, a common mechanism of sport-related concussions occur from aerial challenges related to soccer heading.[24] Furthermore, this thesis demonstrates that the majority of purposeful soccer headers occur from long-range kicks and throw-ins. Clearly, an emphasis on ball control could help to minimize aerial challenges as well as the majority of heading scenarios in youth soccer. Accordingly, this simple coaching strategy could help reduce overall cumulative head impact burden as well as concussion risk in youth soccer.

Neck strengthening has been proposed as a possible modifiable risk factor to reduce head impact accelerations and concussion incidence; however, findings are not consistent across the various studies. One laboratory study reveals that sternocleidomastoid strength significantly predicts both linear and rotational head impact acceleration, while head mass significantly predicts rotational head acceleration.[25] Another study had participants perform eight-weeks of isotonic cervical muscle training, which led to increased neck girth in females, and increased isometric strength in cervical flexors for males, and cervical extensors for females. However, these improvements in neck strength were not associated with decreases in head acceleration.[26] The authors concluded that while participants reveal improvements in neck strength, the neuromuscular changes required to improve dynamic restraint and reduce head acceleration do not occur.

When we consider limiting or restricting heading exposure, the age of the participants must be taken into account. The brain is still developing during adolescence, with distinct immaturities in white matter[27,28] that are more vulnerable to injury. For instance, youths demonstrate an increased number of unmyelinated axonal tracts that are more suspectable to damage compared to myelinated axonal tracts.[29] Currently, there are no studies that empirically investigate the effects of age-dependent restrictions on heading. Clinical evidence has long demonstrated that the developing brain shows unique responses to brain injury compared to adults. Accordingly, research regarding repetitive head impacts in various youth age groups is essential to establishing data-driven guidelines. Future work should be directed towards understanding age-related differences in response to repetitive head impact exposure that will aid in such data-driven models to develop age-relevant clinical management guidelines and identifying risk of brain injury.

There are some limitations that should be considered in this thesis. Firstly, this thesis only assessed purposeful soccer heading in female youth soccer players. Male soccer players experience a greater number of head impacts compared to female players, yet female soccer players sustain larger head impact magnitudes.[4] Accordingly, given such differences, future studies should investigate sex-related differences in response to repetitive head impact exposures. Nevertheless, it is not known whether youth males would show similar EEG findings as demonstrated in this thesis. In addition, due to the nature of the experimental protocol, movement artifact in the EEG signal may have occurred, and accordingly, efforts to minimize signal artifacts were taken. For example, data were manually inspected and segments that contained movement artifacts or excessive muscle activity at any electrode site were eliminated. In addition, independent component analysis was used to remove eye blinks similar to previous work.[12] Our findings are also limited to the frontal electrode regions, and therefore we are unable to comment on other electrodes sites. However, the frontal and temporal lobes appear to be most vulnerable to concussion injury,[30] and disruption in these areas are associated with impaired executive function, learning and memory, as well as behavioral changes.[31]

Given that the EEG device is portable and more affordable compared to other imaging modalities (MRI, DTI), the use of EEG to evaluate head injury is expected to increase. Our EEG results expand on previous work performed on healthy individuals, showing that combined task and cumulative number of headers are associated with greater neural activation in the frontal regions. Such findings could be valuable in developing models to reveal residual neurocognitive deficits associated with repetitive head impacts as well as in sport-related concussion. Yet, whether a correlation exists between repetitive head impacts and concussive injury has not been established. Future research should evaluate the early signs of head injury resulting from cumulative head impact burden across athletes of different ages and sex.

In conclusion, female youth soccer players experience frequent head impacts during a season of soccer, and some of these impacts are comparable to those experienced by collegiate soccer players. Furthermore, the cumulative head impact burden resulting from purposeful soccer heading is associated with underlying subclinical changes that become apparent during combined exercise and cognitive load. This thesis identifies that youth athletes that are exposed to cumulative head impacts exhibit neurocognitive changes, as indicated by EEG. These results provide evidence for the need of data-driven models to identify players at risk for brain injury during the soccer season. Such information could help to establish preventative guidelines through early detection of players at risk for brain injury.

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Curriculum Vitae

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Publications:

1. **Harriss A,** Johnson A, Thompson J, Walton D, Dickey J. A continuous performance task during moderate exercise amplifies the effects of cumulative soccer heading on brain activity in female youth soccer players. Submitted to: Journal of Concussion. Accepted: Febrary,2020.
2. Manning K, Brooks J, Fischer L, Blackney K, **Harriss A,** Brown A, Bartha R, Doherty T, Dickey JP, Jevremovic, T, Barreira C, Fraser D, Holmes J, Dekaban G,

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3. **Harriss A,** Johnson A, Walton D, & Dickey JP. (2019). Head impact magnitudes that occur from purposeful soccer heading depend on the game scenario and head impact location. Musculoskeletal science and practice, 40, 53-57.
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5. **Harriss A,** Abbott K, Humphreys D, Daley M, Moir ME, Woehrle E, Fischer L, Fraser D, & Shoemaker JK. (2019). Concussion symptoms predictive of adolescent sport-related concussion injury. Clinical journal of sport medicine: official journal of the Canadian Academy of Sport Medicine.
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Refereed conference proceedings

1. The effects of moderate exercise and cumulative purposeful heading exposure on electroencephalogram activity in female youth soccer players. ABI, New Orleans, Louisiana, February 2020.
2. Moderate Exercise Can Be Used to Detect Subclinical Changes in Alpha Activity Related to Cumulative Soccer Heading. IBIA, Toronto, Ontario, March 2019.
3. Structural and functional neuroimaging changes in female rugby players with and without a history of concussion. International Society for Magnetic Resonance in Medicine, Montreal, May 2019.
4. The Impact of Aerobic Exercise Training on Autonomic Function During the Acute Phase of Adolescent Sport-Related Concussion. Experimental Biology, San Diego, April 2018
5. Heart Rate and Heart Rate Variability Responses are Similar during Static Exercise in Healthy Seated Adults and Concussed Supine Adolescents. Experimental Biology, San Diego, April 2018
6. The Effects of Subconcussive Impacts on Heart Rate Variability in Female Youth Soccer Players. Experimental Biology, San Diego, April 2018

7. Investigation of Neural Cardiac Dysregulation Using Brief 30% Isometric Handgrip Protocol in Adolescents Diagnosed With Concussion. CASEM-AQMS Sport Medicine Conference, Montreal, June 2017.
8. Comparison of Self-Report Symptom Endorsement Between Acutely Concussed Adolescents and Healthy, Age-Matched Controls. CASEM-AQMS Sport Medicine Conference, Montreal, June 2017.
9. Head Accelerations Experienced From Purposeful Heading Are Equivalent to Non-Header Impacts in Youth Soccer. CASEM-AQMS Sport Medicine Conference, Montreal, June 2017

Conference contributions (other than in refereed conference proceedings)

Conference Abstracts Accepted as Talks

1. Invited speaker. Everything in Sport: Rowan's Law Panel. Vaughan, Ontario, May 2019.
2. Head Impacts in youth soccer: Where do we go from here? Invited Keynote Speaker: First annual QCAC 2018: Prevention, Awareness, and Support. Kingston, November 2018.
3. Evaluating head impacts in youth soccer and improving rehabilitation outcomes with exercise. Invited Speaker: Exercise is Medicine, Spoken Science Speaker Series. March 2018.
4. Head impacts in youth soccer players: Lessons learned from intensively studying a season of soccer. Invited Speaker: National Orthopedic Symposium, London October 2017.
5. Should heading be a part of soccer? Using wearable technology and video analysis to understand head impacts during a youth soccer season. See the Line, London, October 2017.
6. Understanding the Relationship Between Head Impact Exposures and Brain Function in Youth Soccer Players. Ontario Soccer Summit, Trent University, March 2017.
7. We know that soccer has a high rate of concussions, but how large and numerous are the head impacts? Exercise is medicine, June 2016.
8. Wraparound field to finite element modeling approach for evaluating biomechanical responses to head impacts in soccer. Canadian Society of Biomechanics, August 2018.

Conference Abstracts Accepted as Posters

1. Verification of a protocol to quantify athlete-equipment interface forces: an evaluation of applied forces from ice hockey goaltender leg pads. Canadian Society of Biomechanics, August 2018.
2. Autonomic dysregulation in heart rate responses to brief static handgrip exercise in concussed adolescents. Exercise is Medicine Canada National Student Conference. Accepted. London, June 2018.
3. Development and verification of a protocol to quantify athlete-equipment interface forces: an evaluation of applied forces from ice hockey goaltender leg pads. American Society of Biomechanics, March 2017.

4. Head Impacts in Youth Soccer are comparable to American Football. Western Research Forum: Mosiac, Western University, March 10 2017.
5. We know that soccer has a high rate of concussions but how large are these head impacts? Research on Concussion Spectrum of Disorders, Toronto, January 21 2017.
6. Biomechanical Head Impact Exposures in Youth Soccer and the Relationship to Cognitive and Brain Function, Canadian Society of Biomechanics, Hamilton, July 22 2016.
7. We know that soccer has a high rate of concussions, but how large and numerous are the head impacts? Exercise Is Medicine, Western University, June 23 2016.
8. Effects of changes in muscle activation level and spine and hip posture on erector spinae fiber orientation. World Congress of Biomechanics (Boston, July 2014), Western University Bone and Joint Conference (Western University, July 2013).

<u>Other contributions: Invited Lectures, Presentations and Knowledge Translation</u>

1. Abstract: "The impact of aerobic exercise training on autonomic function in adolescent sport-related concussion" selected by the communications committee mainstream media for the 2018 Experimental Biology meeting (San Diego, 2018).
2. Concussion Research at Western University: Prevention and Improving Rehabilitation Treatment. Class: Medical Issues in Exercise and Sport (Kin 4437a), University of Western Ontario, London, Professor: Dr. Lisa Fischer (November 2017)
3. Baseline testing for Western University varsity teams. Fowler Kennedy Sports Medicine Clinic (September 2017). Dr. Lisa Fischer, London Ontario.
4. Public outreach about sport-related concussions in youth sports and baseline testing. Fowler Kennedy Sports Medicine Clinic (September 2017). Dr. Lisa Fischer, London Ontario.
5. Preliminary Findings: Ontario Player Development Head Impact Study (Distributed to Ontario Soccer Association, and Burlington Youth Soccer Club – November 2016)
6. Major Impact – study draws much needed attention to female athletes and concussion risks - Western News (September 2016)
7. Ontario Player Development League: Study Update from Western University (August 2016)
8. Wearable Technology allows researchers to study 'real-time' head impact in soccer – Western News (June 2016)
9. Study to probe head hits' impact in girls soccer – London Free Press (June 2016)
10. The OPDL Spotlight Series – Concussion testing (May 2016)
11. Understanding repetitive head impacts in adolescent females. National radio interviews for CBC News (Edmonton, Victoria, Calgary, Vancouver, Toronto, Kelowna, White Horse, Regina) (May 2016)
12. Guest Lecturer. Joint biomechanics and methodology for calculating shear and compression forces during dynamic movements. SCMA*3100, University of Guelph-Humber (February 2013).