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Consequences of Adolescent Sport-Related Concussion and Musculoskeletal Injury: Examining Long-term Impacts on Body Composition and Physical Activity Levels

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Consequences of Adolescent Sport-Related Concussion and Musculoskeletal Injury: Examining Long-term Impacts on Body Composition and Physical Activity Levels

by

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Abstract

Sport-related concussions (SRC) may be encumbering injuries and are experienced in high rates amongst Canadian adolescents participating in sport. Little is known of the long-term effects of SRC in how they may affect both physical activity behaviors and body composition as adults later in life. This thesis examined appropriate algorithms to employ when utilizing Actigraphs as objective measures of free-living physical activity behaviors, and then the body composition levels and physical activity levels of adults (ages 18-33) with a 5–15-year history of either SRC or musculoskeletal (MSK) injury relative to uninjured controls (UC). Data were collected for 268 individuals participating through the SHRed Consequences of Concussion cohort study. Analyses displayed that SRC and MSK injury cohorts relative to UC had comparable body compositions, identified through lean mass and fat mass indices, as well as comparable physical activity behaviors, denoted by daily amounts of sedentary time and light, moderate, moderate-to-vigorous, and vigorous physical activity. This demonstrated that those with adolescent SRC or MSK injury history continue to participate in physically active lifestyles as young adults as evidenced by either maintaining and/or acquiring body compositions and participating in physical activities similar to those without injury history. Future research should take a more granular look at long-term sport-related injury through examining persistent concussion symptoms for those with SRC history as well as type/location of MSK injury in an effort to consider the heterogeneity of these injuries.

Keywords: sport-related concussion, young adult, adolescent, long-term health, physical activity, physical activity behaviors, body composition, adiposity.

Preface

The Actigraph algorithm validation study (Chapter 3) included in this thesis was completed within the University of Calgary's Human Performance Laboratory through word-of-mouth recruitment prior to employing Actigraph algorithms in Chapter 5. Chapters 4 and 5 were completed in-part of the SHRed Consequences of Concussion cohort study (REB21-0548). The objective of the larger cohort study was to examine long-term sequalae of SRC through numerous outcomes across function, physiological, psychosocial, neuropsychological, and clinical domains. This thesis was completed to examine body composition and physical activity behaviors within the functional arm of the SHRed Consequences of Concussion cohort study.

Chapter 3. ***Validity of GT3X+ ActiGraph algorithms for physical activity intensities in young adults using a modified Buffalo Concussion Treadmill Test (2024).*** Leggett B, Burma JS, Galarneau JM, Smirl JD, Emery CA. Leggett et al. are in the process of submitting this manuscript for publication in an academic journal. Benjamin Leggett was the first author and contribution to this study involved conceptualization, recruitment, data collection, data processing, statistical analyses, writing, and editing.

Chapter 4. ***Consequences of sport-related concussion: Exploring long-term adiposity (2024).*** Leggett B, Galarneau JM, Smirl JD, Emery CA. List of authors has not been finalized. Leggett et al. is awaiting the formal conclusion of the SHRed Consequences of Concussion cohort study to include the final participants in the analyses and manuscript. Benjamin Leggett is the first author and contributed to study and manuscript conceptualization, recruitment, data collection, data processing, statistical analyses, writing, and editing.

Chapter 5. ***Consequences of sport-related concussion: examining physical activity behaviours (2024).*** Leggett B, Galarneau JM, Smirl JD, Emery CA. List of authors has not been finalized. Leggett et al. is awaiting the formal conclusion of the SHRed Consequences of Concussion cohort study to include the final participants in the analyses and manuscript. Benjamin Leggett is the first listed author and contributed to study and manuscript conceptualization, recruitment, data collection, data processing, statistical analyses, writing, and editing.

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Dedications

I would like to dedicate the following thesis, in-part, to my father, Grant, whom my family lost to suicide 14 years ago. While the work I had the opportunity to complete within the Sport Injury Prevention Research Centre may not be directly related to the role you played in my life, the drive I have held for achieving more through academia and goals towards working in healthcare are something you blessed me with. I promise to honor your legacy and name in every way I can.

To my mother and brother, Carey and Jeremy, I would like to dedicate my thesis as whole to you. I simply would not be here without the both of you. Your patience, love, care, and support are the only reasons I have had the opportunity to do anything as an adult, as adolescence challenged me far beyond the abilities I then possessed. Mom, I do not expect you to read this dry document, but know it exists because you made hard decisions that I will always be thankful for. You command a respect from me no words can describe and please know that you did beautifully by my brother and me. Without hesitation or fail your care has allowed us both to do incredible things with our lives and we owe everything to you.

Table of Contents

List of Symbols, Abbreviations, & Nomenclature

ACSM	American College of Sports Medicine
AE	Athletic Exposure
ACL	Anterior Cruciate Ligament
BCTT	Buffalo Concussion Treadmill Test
BMI	Body Mass Index
CHMS	Canadian Health Measures Survey
CI	Confidence Interval
CISG	Concussion in Sport Group
CPM	Count Per Minute
CSEP	Canadian Society for Exercise Physiology
DXA	Dual Energy X-Ray Absorptiometry
FFMI	Fat-Free Mass Index
FMI	Fat Mass Index
HRR	Heart Rate Reserve
IRR	Incidence Rate Ratio
kg	kilogram
LMI	Lean Mass Index
LPA	Light Physical Activity
IR	Incidence Rate
PA	Physical Activity
MET	Metabolic Equivalent Task
min	minute
ml	millilitre
MPA	Moderate Physical Activity
mTBI	Mild Traumatic Brain Injury
MSK	Musculoskeletal
MVPA	Moderate-to-Vigorous Physical Activity
PA	Physical Activity
NHANES	National Health and Nutrition Examining Survey
VPA	Vigorous Physical Activity
QoL	Quality of Life
SB	Sedentary Behaviour
SRC	Sport-Related Concussion
UC	Uninjured Control

Chapter 1. Introduction and Rationale

1.1 Background

Participation in physical activity (PA) behaviours has been extensively studied and shown to provide numerous health benefits for both youth and adults, extending well beyond improved physical health. Improvements in cognitive function, emotional well-being, social health, and perceptions of psychological well-being have been identified to be associated with PA behaviours [1, 2]. Adolescent sport participation is associated with lower cardiometabolic risk and improved mental health outcomes later in life [3]. Moving to quantify PA behaviours associated with both physical and psychological health benefits, 60-minutes of daily moderate-to-vigorous PA (MVPA) has been shown to improve both in children and youth (11-17 years of age) [4]. Additionally, through an assortment of mechanisms such as improved synaptic plasticity, perfusion, and neurogenesis, PA has been shown to delay age-related cognitive decline in adults [5-7].

With positive youth PA behaviours and engagement in mind, it is critical to encourage participation in activities that are found to be enjoyable with feelings of competency that may help optimize motivation for sustaining positive PA behaviours in order to reap the rewards of associated health benefits [8]. However, it is important to note that a major concern with regards to sport participation, a common means for youth engagement in positive PA behaviours, is an increased risk of injury and the potential subsequent associated burden of injury. Up to 1 in 3 youth in Canada seek required healthcare attention annually and up to 1 in 3 American working adults end up missing at least day of work due to sport-related injuries [9-11]. Sport-related injuries may occur through either a traumatic sudden-onset [considered to be those from an identifiable event (eg, fracture-causing collision during sport)], or gradual onset [considered those that lack an identifiable event (eg, tendinopathy resulting from repeated sport-related movements)], each of which may result in a broad range of physiological consequences and physical burden [12, 13]. The numerous benefits of positive PA behaviours, including engagement in regular moderate typo vigorous PA, have been shown to typically outweigh the risks at appropriate levels and intensities [14], however there is still well-established risk of injury during youth sport participation.

1.2 Sport-Related Concussion

A sport-related concussion (SRC) is a transient disruption in neurological function induced by biomechanical forces transmitted to the brain by either a direct or indirect blow to the head or body [15]. SRC is considered to be among the most complex injuries for medical professionals to assess, diagnose, and manage. This is largely due to the invisible nature or this injury and typically involves healthcare practitioner assessment of its clinical signs and symptoms, as there are currently no gold-standard biomarker based objective assessment tools [15]. Furthermore, SRCs are also extremely common as an estimated 1 in 9 Canadian youth sustain a concussion every year, with risk of concussion increasing when participating in contact or collision sport [9, 16]. A systematic review examining concussion incidence rates (IR) amongst adolescent (ages 10-19) athletes per 1000 athletic exposures (AE) identified the top three sports as rugby (IR=4.18;95% CI 2.50-5.86), ice hockey (IR=1.20;95% CI 1.00-1.31), and American football at (IR=0.53;95% CI 0.040-0.67) [17]. Conversely, the sports with the lowest identified concussion IRs in adolescent athletes per 1000 AEs were volleyball (IR=0.03;95% CI 0.00-0.05), baseball (IR=0.06;95% CI 0.04-0.08), and cheerleading (IR=0.0;95% CI 0.04-0.09). While examining 2002 to 2018 Alberta and Ontario emergency department (ED) visits, the Public Health Agency of Canada has identified 80.7% of concussions among females and 85.8% of concussions among males to present in individuals between 5 and 29 years of age [18]. Among 10 to 14 year olds, the highest concussion

IRs presenting to the EDs were found to be a result of participation in non-collision ball sports (i.e., basketball, volleyball) for females (95.3 concussions per 100,000 individuals) and ice hockey for males (203.7/100,000) [18]. Among 15 to 19 year olds, rugby/football were second (66.4/100,000) to non-collision ball sports (72.9/100,000) in females, and similarly football/rubgy were second (119.2/100,000) to ice hockey (150.7/100,000) regarding concussions in males presenting in EDs [18]. These findings further implore that despite facilitating beneficial PA behaviors in youth, sport-participation is a risk factor for concussion.

While a typical recovery from SRC takes 10-14 days for adults and 14-28 days in children, up to 30% of children and adolescents remain symptomatic for 1-month or more post injury [15, 19]. However, in the context of changes to PA or PA behaviors after SRC injury, little has been established beyond identifying that those who do engage in PA post-SRC injury have improved recovery trajectories and are more likely to achieve resolution of symptoms [15, 20, 21]. There is limited research suggesting that up to 6-months post mild traumatic brain injury (mTBI) or concussion (terms used often interchangeably) [22], adolescents and young adults (12-25 years of age) are less likely than matched orthopaedic injured or healthy controls to meet movement guidelines [23]. This suggests that concussion injury and concussion injury recovery trajectory may influence PA or movement behaviours in longer term settings.

1.3 Consequences of Long-Term Sport-Related Concussion

1.3.1 Physical Activity Behaviours After Sport-Related Injury

There is a paucity of research examining PA behaviours in the context of longer-term (5-15-year) SRC injury history. Existing knowledge surrounding acute SRC, or longer-term sport-related injury may help shed light on why inquiry into adolescent SRC and its effects on PA behaviors in adulthood are relevant. Previously, exertional testing quantifying exercise tolerance to ascertain intensity thresholds of PA associated with symptom exacerbation has been shown to aid in the management and recovery trajectory of concussion in acute settings [24-28]. Thus, the benefits of adequate PA post-SRC injury on recovery are well established. While examining 3-12 year sport-related musculoskeletal (MSK) injury history and how it may affect PA behaviours, objective accelerometer measured MVPA levels have been observed to be lower in those with injury history [-13.5 (95% CI -25.6, -1.4)] than controls, where females also engaged in 10.8 min (95% CI -20.2, -1.4) less MVPA than males [29]. This research may suggest that should SRC be comparable to MSK injury, one might expect similar decreases in long-term PA levels post SRC injury as well as differences between sexes. Additionally, psychosocial factors may influence reduced sport participation after SRC injury as both athlete and parent fears of recurrent injury as well decreases in self-efficacy have been previously identified after adolescent SRC [30-32]. This means future research should be aimed at understanding how SRC injury history affects long-term PA levels, how this may compare to both MSK injury history as well as healthy controls, and what correlates like sex impact these changes to PA behaviours.

1.3.1 Adiposity After Sport-Related Injury

Previous research has demonstrated that increases in adiposity are associated with higher risk of adverse health outcomes such as cardiovascular disease, diabetes, metabolic disease, some forms of cancer, and musculoskeletal disorder/disease [33-35]. Similar to examination of adult PA behaviours after adolescent SRC, there is an apparent gap in the literature describing measures of adiposity. However, in referencing existing research on the effects of longer-term (3-12-year) knee injury on measures such as body mass index (BMI) and fat mass index (FMI), we might expect to see similar differences [36]. When compared to matched uninjured controls, injured individuals with 3-12-year knee injury history had a 1.79 (range: 0.94 - 2.63) higher BMI, 2.3% (range: 0.97 - 3.63) higher fat mass, and 1.05 (range: 0.53 - 1.57) higher fat mass index (FMI; kg/m^2) [36]. Thus, with the adverse effects of increased adiposity being well established and evidence suggesting long-term MSK injury may result in higher levels of adiposity, examination into the effects long-term SRC injury may have on adiposity, relative to MSK injury and healthy controls, is warranted.

1.4 Research Rationale

While factoring in the economic burden placed on individuals and the healthcare system because of concussion, in addition to the well-understood detrimental adverse changes to PA behaviours and adiposity may have on health, it is crucial that inquiry be made into understanding the true long-term effects of SRC injury experienced in youth. In the context of PA behaviours, physical inactivity, and associated obesity, healthcare costs are estimated to be in the billions [37]. Thus, the connection between long term concussion history in youth, where sport-participation and SRC rates are well-established, and changes to PA behaviours, as well as the correlates to this connection, need to be examined. Additionally, this examination should involve a comparison group such as MSK injured individuals as previous literature has already identified MSK injury experienced in youth to be associated with changes to PA levels and adiposity-related measures in settings as long-term as 12-years.

1.5 Purpose

The objective of this thesis is to examine the long-term (5-15 year) consequences of SRC injury experienced in youth (ages 11-18), and in particular outcomes related to physical activity, physical inactivity, and adiposity. The age of initial sport-related injury (11-18 years) was selected as significant amounts of development and both structural and functional maturation occur during adolescence and may characterize an increased vulnerability within the brain [38-43]. Following up 5-15 years after initial injury helps capture health-related outcomes of individuals entering adulthood, as well as the ≥5-year post-injury gap described in literature described by systematic review examining long-term sequalae after concussion [15, 44, 45]. The first study of this thesis examines the validity of commonly used Actigraph algorithms that determine and quantify objectively measured PA levels using tri-axial linear accelerometry. This will be done through comparing physiologic measures with respective algorithms during a laboratory-administered incremental exercise test known as the Buffalo Concussion Treadmill Test. The second study of this thesis seeks to examine within a sub-sample of full study recruitment cardiorespiratory fitness in relation to PA and adiposity levels in individuals with a 5–15-year history of SRC, while comparing outcomes of those with SRC history to both those with a 5–15-year history of MSK injury as well as healthy controls with no significant injury history. The third study of this thesis seeks to examine PA behaviours at a variety of movement intensities, as well as sedentary behaviours and body composition in the full sample of individuals recruited with a 5–15-year history of SRC, while comparing outcomes of those with SRC history to both those with a 5–15-year history of MSK injury as well as healthy controls with no significant injury history.

1.5.1 Specific Primary Objectives

1.5.1.1 Chapter 3 ***(Validity of GT3X+ ActiGraph algorithms for physical activity intensities in young adults using a modified Buffalo Concussion Treadmill Test).***

1. To identify which algorithm more appropriately defines physical activity intensities [light, moderate, vigorous, and MVPA] when compared to Canadian Society for Exercise Physiology (CSEP), American College of Sports Medicine (ACSM), and metabolic equivalent task (MET) guidelines in 20 [10 male, 10 female] individuals that completed modified Buffalo Concussion Treadmill Tests.

1.5.1.2 Chapter 4 ***(Consequences of sport-related concussion: Exploring long-term adiposity***

1. To examine the association between body composition and SRC injury history via fat mass index [FMI: fat mass (kg)/height (m^2)] and lean mass index [LMI: lean mass (kg)/height(m^2)] in individuals with a 5-15 year history of SRC experienced in youth, compared to individuals with 5-15 year history of MSK injury and uninjured controls.

2. To examine the role in which sex, age, time since injury, and time loss from injury effect FMI and LMI outcomes.

1.5.1.3 Chapter 5 (*Consequences of sport-related adolescent concussion: examining 5–15-year physical activity behaviours and adiposity)*

1. To examine the association between MVPA [daily time (mins)] and SRC injury history in individuals with a 5-15 year history of SRC experienced in youth, compared to individuals with MSK injury history and health controls.

2. To examine the association between sedentary activity [daily averages (mins)] and other PA behaviours like light intensity PA in individuals with a 5-15 year history of SRC

experienced in youth, compared to individuals with MSK injury history and health controls.

3. To examine the role in which sex, age, time since injury, and time loss from injury effect PA outcomes.

1.6 Summary of Thesis Format

Chapter 2 is a literature review examining what research exists regarding the relationship between PA behaviours, adiposity, and concussion history. Chapter 3 examines the validity of two Actigraph algorithms used to quantify PA levels in both youth and adult populations using a modified Buffalo Concussion Treadmill Test, with the intention of employing findings from this investigation in Chapter 5. Chapter 4 examines the consequences of SRC injury experienced 5-15 years ago in youth (ages 11-18) in the context of associations of SRC injury history with adiposity. Chapter 5 examines the consequences of SRC injury experienced 5-15 years ago in youth (ages 11-18) in the context of associations of SRC injury history with PA. Chapter 6 summarizes the findings from Chapter 3, 4, and 5, discusses the implication(s) of the findings, and comments on future research directions regarding concussion injury experienced in youth and the consequences it may have on PA behaviours and adiposity later in life.

Chapter 2. Literature Review

2.1 Introduction

The purpose of this literature review is to examine what research exists regarding the relationship between physical activity behaviours, adiposity, and concussion injury history, while using musculoskeletal injury history as a comparison for what relationships may be expected. The goal is to identify significant correlates that may affect these relationships and describe research relevant to understanding the long-term (5-15 year) consequences of sport-related concussion experienced in youth (aged 11-18).

2.2 Sport-Related Concussion

The Concussion in Sport Group (CISG) characterizes sport-related concussion (SRC) as a transient disruption in neurological function induced by biomechanical forces transmitted to the brain by either a direct or indirect blow to the head or body [15]. The consensus statement and systematic review on potential later in life consequences of concussion from the 6th International Consensus Conference on Concussion in Sport draws light to the reality that multifaceted research and funding need to be placed in developing a greater understanding of long-term athlete health after concussion [15, 45]. Specifically, the consensus statement suggests future well-designed case-control and cohort studies be used as they allow for individual risk-modifying and confounding factors to be included when examining association between sport participation during adolescence and long-term neurological or cognitive impairment [15, 45]. Long-term in the context of CISG review statements and this literature review is described by a ≥5-year concussion injury history [45]. The CISG identifies SRC as a form of traumatic brain injury to provide a consistent definition for the conceptual definition of concussion, which is often referred to as mild traumatic brain injury [15]. However, the CISG delineates the diagnostic definition of concussion from the American Congress of Rehabilitation Medicine (ACRM) definition of mTBI [46]. This allows for an athlete with a biomechanically plausible mechanism of injury presenting with acute symptoms and not clinical signs of concussion to be considered having sustained an SRC [46]. SRC is considered among the most complex injuries in sports medicine to diagnose, assess, and manage due to the inherent functional vs structural and heterogeneous nature of this injury [15].

Clinically, the presentation of concussion includes signs and symptoms that reflect a disturbance to the physiological homeostasis of the body. Diagnosis of a suspected concussion typically involves the assessment of its clinical signs and symptoms which may affect the somatic, cognitive, physical, balance, and sleep domains [15]. Signs and symptoms of disruption to these domains may present as but are not limited to, respectively, headache, feeling slowed down, loss of consciousness, impaired balance, and hyper- or hyposomnia [15]. Adults typically recover 10-14 days after injury, however up to 30% of individuals may experience new or worsening symptoms at the 3-month post-injury timepoint [47, 48]. Regarding adolescents (11-19 years), those who have sustained a concussion typically recover 14-28 days post-injury [15], with 30% of children and adolescents reporting persistent symptoms 1-month post-injury [19, 48]. These findings and CISG review statements suggest that concussions are both common and serious and need to be examined both in the context of immediate recovery as well as long-term ≥5 year health outcomes later in life [15, 45, 48].

2.3 Sports Injury and Concussion in Canadian Adolescence

This literature review will be utilizing World Health Organization (WHO) definitions for adolescence (11-19 years old), children (<18 years of age), and youth (15-24 years old) to standardize these demographic terms that have been used extensively in previous literature [4, 49-52]. Sport-related injuries in the aforementioned demographics may occur through either a traumatic sudden-onset [considered to be those from an identifiable event (eg, fracture-causing collision during sport)], or gradual onset [considered those that lack an identifiable event (eg, tendinopathy resulting from repeated sport-related movements)], each of which may result in a broad range of physiological consequences and physical burden [12, 13]. Sudden onset injury may occur through acute or repetitive mechanisms through direct contact (immediately leading to a health issue) or indirect contact (health issue as a result of incidental force contributing to a causal chain), whereas graduate onset injuries may present from only repetitive non-contact mechanisms [13].

Sport-related injury may be defined as any tissue damage or derangement of normal physical function as a result of sport participation [13]. Sport-related injury has been identified to be the leading cause of injury in adolescence in Canada [9] with an estimated 3 million people sustaining a concussion injury from sports or recreation activities in North America annually [53]. Fifty percent of these estimated 3 million North American injuries are sustained by children or adolescents [53]. Overall, it is estimated that 1 in 9 (11.1%) of Canadian youth experience a concussion every year, with risk increasing when participating in contact or collision sport(s) [9, 54]. Furthermore, a concussion can potentially be a debilitating injury affecting the physical, mental, financial, and academic well-being of an individual, as well as their family and friends [55]. However it should be noted, that collision sport youth athletes such as those engaged in rugby, ice hockey, and football experience the highest risk of suffering a sport-related concussion (SRC), with incidence rates often exceeding the aforementioned Canadian youth average [54]. Systematic review examining the incidence rates (IR) of concussion amongst primarily male youth athletes by 1000 athletic exposures (AE) identified the top three sports as rugby, ice hockey, and American football at 4.18 (95% CI 2.50-5.86), 1.20 (95% CI 1.00-1.31), and 0.53 (95% CI 0.040-0.67), respectively [17]. Conversely, the sports with the lowest identified IRs of concussion in youth athletes per 1000 AEs were volleyball, baseball, and cheerleading, at 0.03 (95% CI 0.00-0.05), 0.06 (95% CI 0.04-0.08), and 0.07 95% CI 0.04-0.09), respectively [17]. While examining 2002 to 2018 Alberta and Ontario emergency department (ED) visits, the Public Health Agency of Canada has identified 80.7% of concussions among females and 85.8% of concussions among males to present in individuals between 5 and 29 years of age [18], suggesting this age range where sport-participation is high is at the highest risk. Among 10 to 14 year olds, the highest rates of concussion presenting in EDs were found to be a result of participation in non-collision ball sports (i.e., basketball, volleyball, etc) for females (95.3 concussions per 100,000 individuals) and ice hockey for males (203.7/100,000) [18]. Among 15 to 19 year olds, rugby/football were second (66.4/100,000) to non-collision ball sports (72.9/100,000) for females, and similarly football/rubgy were second (119.2/100,000) to ice hockey (150.7/100,000) regarding concussions for males presenting in EDs [18]. These data suggest that the incidence of concussion is high in individuals who participate in sport, and that incidence of concussion may be higher in contact and collision sport. Knowledge of these injuries frequently and predictably occurring should prompt inquiry into health-related consequences of concussion injury in both acute and long-term (≥5 year) contexts [45, 48]. While extensive research has gone into describing and quantifying risk in several different ways, there is a gap in existing literature examining individuals with a longer-term history of adolescent concussion and this leaves much to be examined and established by future research.

2.4 Brain Development and Vulnerability to Concussion During Adolescence

Neurological development does not occur at consistent rates across the human lifespan, where full maturity of the nervous system is believed to be achieved between 30 and 40 years of age [39-41]. Consequently, the human brain goes through significant amounts of development and both structural and functional maturation during adolescence [38-43]. During this period, the brain undergoes synaptic pruning, myelination, and synaptic organization, leading to long-lasting structural changes [56, 57]. The prefrontal cortex is responsible for cognitive control and decision-making, and it is a brain region that experiences substantial development during adolescence [58]. Further, the social brain, which characterizes the ability to understand and navigate social interactions, also develops during this adolescent period [42]. Myelination continues to occur during adolescence in areas such as the temporal lobes and prefrontal cortex [59], which is associated with executive functions such as goal setting and inhibition of impulsive behaviours [38]. Considering current understanding of the pathophysiology of concussion is centered around a neuronal energy crisis catalyzed by neuronal and in particular axonal damage as a result of a concussive blow [60], it is reasonable to suggest that the adolescent brain may be particularly vulnerable to damage as it is in a heightened developmental stage. Further, neurochemical, neurophysiological, and neurobehavioral inquiry has indicated the adolescent brain may be vulnerable to damage potentially causing disrupted growth and maturation [61].

A systematic review has identified a relationship between age and clinical recovery after concussion, where high school athletes recover at a slower rate when compared to collegiate or professional athletes [62]. This clinical finding may also highlight an adolescent vulnerability to concussion as a more well-developed neurological system associate with increased age may improve recovery trajectory in the acute setting. Consequently, in the context of this literature review and examining potential long-term sequalae of SRC, it is important to understand how or if adolescent concussion may affect behaviours such as physical activity directly or indirectly as well as adiposity-related outcomes, as they are generally understood to have effects on a myriad of aspects of health and well-being.

2.5 Physical Activity Behaviours

Physical activity (PA), sleep, and sedentary behaviour are all PA behaviours that may occur throughout a 24-hour window. PA can be defined as a bodily movement produced by skeletal muscles that requires energy expenditure [63]. PA may comprise several different activities, such as sports participation, movement involved in daily activities, or exercise. Exercise and PA are often used interchangeably, however there are distinct differences between the two. PA refers to any bodily movement requiring energy expenditure, however, exercise is a subset of PA that is structure, planned, and repetitive, with the intention of improving or maintain physical fitness [64]. Sport-participation may be described as a PA behaviour, where training for sport may involve exercise-related goals designed to improve cardiovascular fitness, strength, flexibility, or endurance [64]. Sedentary behaviour (SB) may be viewed as the reciprocal of PA as it describes non-active behaviours, these being characterized by minimal energy expenditure and little-to-no physical movement. As such, SB may be defined as any waking behaviour that requires an energy expenditure ≤1.5 metabolic equivalents (MET), often in a sitting or reclined posture [65]. METs are a common objective measure of energy expenditure, where one MET is equivalent to the energy expended while sitting at rest, which is a standard of 3.5 mL of oxygen per kilogram of body weight per minute [65]. Young et al. (2016) also delineate SB from a lack of moderate-to-vigorous PA (MVPA), considering it a separate entity.

Adolescent sport participation has been identified to be associated with lower cardiometabolic risk and improved mental health outcomes later in life [3]. Moving to quantify PA behaviours associated with physical and psychological health benefits, 60-minutes of daily MVPA has been shown to improve these outcomes in adolescents (11-17 years of age) [4]. Regular PA has been extensively studied and provides numerous benefits for overall health and well-being. Engaging in PA can reduce the risk of developing chronic diseases such as heart disease, stroke, and diabetes [66], and can also improve mental health and cognitive function [67]. Through an assortment of mechanisms such as improved synaptic plasticity, perfusion, and neurogenesis, PA has been shown to delay age-related cognitive decline in adults [5-7]. The health benefits of PA extend well beyond physical health. Improvements in cognitive function, emotional well-being, social health, and perceptions of psychological well-being have been identified to be associated with PA behaviours [1, 2]. The numerous benefits to PA behaviours have been shown to typically outweigh the dangers despite well-established risk of sport participation discussed above [14].

To characterize the other crucial aspect of PA behaviours, the negative consequences of SB may include reduced cardiovascular health, where SB may also increase the risk of obesity and hormone-related cancer(s) through decreased lipoprotein lipase activity, altered hormone levels, lessened lipid and carbohydrate metabolism, and decreased insulin sensitivity [68]. A systematic review examining SB reports a strong association between SB and both childhood and adolescent obesity [69]. Some research has examined timing and frequency of sedentary bouts in addition to total sedentary time, however length, intensity, and frequency of sedentary bouts have been noted to provide crucial information total sedentary time does not [69-72]. Accumulation of sedentary time in bouts of 60-89 minutes and equal to or greater than 90 minutes may not be associated with mortality after adjusting for the amount of sedentary time accrued in bouts of 1-29 minutes [69-

72]. This suggests that sedentary time need not be accumulated in lengthy bouts and may even suggest that bouts less than 30 minutes, and even as short as 5 minutes, are worth examining in the context of generalized health outcomes and overall mortality [73-75]. Thus, in the context of describing PA behaviours in a given population it seems warranted to also ensure that SB and sedentary bouts are described, due to their implications towards negative health-related outcomes. Subsequently, it is imperative that both SB and PA behaviours be examined in the context of long-term injury history when attempting to effectively describe the effect(s) adolescent injury and/or concussion may have on health-related outcomes in adulthood.

With youth PA behaviours and engagement in mind, it is critical to encourage participation in activities found to be enjoyable, with feelings of competency that may help optimize motivation for sustaining PA behaviours in order to reap the rewards of associated health benefits [8]. It also is important to acknowledge barriers to participation with regards to PA as PA behaviours may be best tailored to individual activity levels, health statuses, and physical function. The health benefits of PA are well understood in the current body of literature and a meta-analysis has also been conducted to examine how PA and mental health are consistent across different life domains (i.e., transportation-, work-, leisure-, school-, and physical education-related PA) [76]. White et al. (2017) sought to look past the known physical health benefits of PA and examined the mental health benefits, where they identified promoting PA during leisure time as a strong correlate to improved mental health. Leisure time activity was then subsequently compared to other PA domains where it was identified as potentially being the most beneficial with regards to mental health promotion and prevention of mental ill-health [76]. Mental ill-health is characterized by lower self-esteem, struggling to maintain interpersonal relationships, and a higher risk of communicable and non-communicable diseases when compared to those not experiencing mental ill-health [76].

These findings suggest engaging in PA modalities as a form of leisure activity may have the same physical health benefits as non-leisure PA but may be associated with improved mental health outcomes. This alludes to the context of a physically active lifestyle where PA is also a part of one's leisure time being an important factor beyond merely meeting activity guidelines. Furthermore, PA is established to be an important aspect of health and in the context of this literature review the extent to which any injury may affect PA behaviours should be examined in order for effective evidence-driven advocacy regarding participation in these behaviours, or conversely addressing barriers to participation.

2.5.1 Physical Activity and Physical Activity Intensities

In the context of Canadian youth, failing to meet guidelines for PA, SB, or sleep is associated with poorer health outcomes when compared to meeting guidelines for all three behaviours [77]. Recommended guidelines for PA behaviours in Canada are defined by the Canadian Society for Exercise Physiology (CSEP), which publicly funded organization and is a resource for translating advances in exercise and PA science into the promotion of both fitness and health outcomes for Canadians. The CSEP has outlined PA guidelines for Canadian adults (ages 18-64), which include but are not limited to: accumulation of 150-minutes of MVPA per week, muscle/strength training activities at least twice per week, and several hours of light physical activities [78]. As per CSEP guidelines, light, moderate, and vigorous PA are defined respectively as 20-40% heart rate reserve (HRR), 40-60% HRR, and 60-85% HRR [79], where HRR is calculated by taking the difference between the estimated maximal heart rate [220 – (age in years)] and an individual's resting heart rate.

While often viewed as less meaningful than MVPA, light PA independently and while adjusting for covariates such as moderate and vigorous PA has been linked to perceptions of positive overall physical health and well-being, as well as to the reduction of health risks such as cardiovascular disease, cancer, and mental ill-health, all while benefiting brain health through upregulation of neuroprotective factors particularly in regions of the brain with high oxidative demand [80-84]. What this suggests is that independent from other intensities of PA like MVPA, light PA is a PA behaviour that should be included in any PA behaviour examination. In the context of this literature review, this means potentially including light PA as an outcome measure, as well as a covariate in the analysis of PA behaviours like MVPA that are often viewed as more impactful on general health, is warranted.

MVPA has been extensively studied globally and the ways in which it may improve health are generally well understood. The Surgeon General's (1996) report highlighted nearly 30 years ago that MVPA has been linked to significant improvements in overall health [85]. More recently, research into MVPA during and post the COVID-19 pandemic has revealed that higher pre-COVID MVPA levels had positive effects on general mental health and MVPA behaviours may be associated with a dampening effect of unique biopsychosocial stressors affecting mental health [86, 87]. As a whole, MVPA itself has been associated with improvements in overall well-being, mental health, cardiovascular fitness, physical independence in older adults, and quality of life all while reducing incidence of metabolic syndromes, cardiovascular diseases, and numerous other chronic diseases [85, 88-91]. However, despite such strong and well documented association between MVPA and overall positive health-related outcomes, it has been suggested that all movement behaviours that can exist within a 24-hour period (i.e., light PA, moderate PA, MVPA, vigorous PA, and SB) should be both examined and promoted accordingly in an integrated approach to address public health crises [88, 92, 93]. In all, evidence related to MVPA heavily suggests that it should be of primary interest while examining PA behaviours in any context. However, only examining MVPA and omitting the examination of other PA behaviours may limit how effectively PA behaviours are being observed, recorded, and interpreted. Thus while examining long-term sports-related injury history in adults whom sustained injury during their youth, all PA behaviours that may fall within a 24-hour window [92] should be examined.

Positive PA behaviours (i.e., engaging in PA, lower sedentary time, etc.) are associated with reducing the risk of at least 25 chronic diseases as well as the risk of premature mortality [78, 94], and as such, the Canadian Health Measures Survey (CHMS) examined the PA levels and habits of Canadian adults from 2007 to 2017 using accelerometer-based PA outcome measures [95]. Here, the intention was to collect a nationally representative sample of adults (18-79 years old) and examine daily minutes of moderate, vigorous, and MVPA [95]. MVPA accumulation was assessed in clinically significant bouts of at least 10-minutes and adherence to the Canadian PA Guidelines (i.e., accumulating ≥150 minutes/week of MVPA, strength training ≥2 times/week, <3 hours/day recreation screen time, etc.) was examined [78, 95, 96]. The results of the CHMS examining PA in Canadian adults identified just 16% of adults met the current PA guidelines of at least 150 minutes per week of MPVA when interpreting activity in bouts of at least 10 minutes. However, 44.8% met the guideline requirements of 150 minutes per week of MVPA when examining all activity irrespective of activity bout duration [95]. Regarding the younger Canadian adults (ages 18-39), data from 2016-2017 revealed males on average engaged in 15 minutes/day (95%CI: 11, 19) of MVPA, with a mere 18.4% (95%CI: 11.1, 28.9) meeting weekly activity guidelines [95]. It was noted, women of the same age range engaged in just 11 minutes/day (95%CI: 7, 15) of MVPA, however the data was deemed too unreliable to publish regarding the proportion of females in this age-range meeting weekly PA guidelines. This may be due to markedly higher variance seen in a less precise confidence interval, possibly as a result of a lower sample size for 18- to 39-year-old women as reflected by the lowest overall participation of any of the five cycles.

Strengths of Clarke et al.'s (2019) study are demonstrated through utilizing accelerometer-based PA data as an objective outcome measure with robust sample sizes ranging from 2,355 to 2,959, depending on which cycle (reflecting time interval). This may allow for stronger generalization to the Canadian population with regards to understanding what proportion of individuals are meeting PA recommendations, how much PA they are engaging in, and removes potential reporting or social desirability bias resulting from self-reported measures. Individuals reporting their own PA participation rates through subjective measures such as the Global PA Questionnaire (GPAQ) have shown good reliability and validity, however validation against objective measures like accelerometer or observed behaviours show weaker results [97]. A limitation of the results was indicated by the authors in reporting which estimates were too unreliable to be published, which should be used with caution, and which estimates had coefficients of variation greater than 33.33%. This may have been a result of how the analysis was stratified by both sex (male, female) and age range (18-39, 40-59, and 60-79 years) which created six sex-age strata which reduced group sizes significantly. Another limitation is placed by the potential for selection bias, where the type of individual willing to participate in this part the CHMS is not speculated on. Additionally, with five different cycles/time periods, there is potential for data to be non-independent from each other and that some data would represent repeated measures if the same individual participated in the survey again. This potential was not speculated on in the methodology or statistical analysis and ultimately reduces the ability to effectively compare year-year or cycle-cycle results. Ultimately, the use of objective PA outcome measures such as accelerometers shows promise in examining PA behaviours. Clark et al. (2019) speculated on the potential for underestimation based on the parameters these devices use to classify activity levels and suggested that thorough thought needs to be placed in how this data is utilized. However, systematic bias such as underestimation of PA as a result of parameters like an algorithm used to classify objectively recorded activity levels can be adjusted for, displaying a strong advantage of an objective measure when compared to subjective or self-reported measures. These findings highlight that accelerometers are an effective way examine and quantify PA levels in adults of all ages, allowing for speculation on PA behaviours in, and for the purposes of this thesis, previously SRC injured (≥5 years ago) populations whom lack significant inquiry [15, 45].

2.5.2 Concussion and Physical Activity

There is a paucity of literature examining the longer-term (greater than 2 years post-injury) effects of concussion (inclusive of SRC and mTBI) on PA, which is consistent with review examining all later-in-life sequalae after concussion [45]. There is also a gap in the literature examining the consequences of concussion beyond the acute post-injury setting in the context of PA levels. This gap specifically is a lack of examination of objective outcome measures seeking to examine and quantify PA levels in individuals with a history of concussion. Systematic review and meta-analysis have demonstrated that appropriate amounts of post-injury PA have a positive association with symptom resolution after concussion [20]. Additionally, utilizing exertion testing to quantify exercise tolerance and ascertain intensity thresholds of PA associated with symptom exacerbation has been shown to aid in both the management and recovery trajectory of concussion

[24-28]. These consistent findings suggest appropriate PA intensity and duration following concussion injury improves recovery trajectory. Therefore, PA can aid recovery from SRC and acts as an early clinical intervention, and as such further understanding of PA behaviours in those with a history of concussion is fundamental.

As already stated, there is a paucity of literature examining PA behaviours in individuals with a history of concussion, specifically, using objective and direct outcome measures. These measures would prospectively allow for a direct quantification and understanding of movement behaviours through examining PA time and intensities. However, some research using indirect measures within two-year windows after concussion injury may help shed light on the importance of understanding the long-term consequences of SRC. A cross-sectional examination of PA, fatigue, and sleep in Dutch adolescents and adults (ages 12-25) 6-months post-mTBI found that when compared to orthopedic injury (OI), those with mTBI history report meeting PA recommendations less frequently [23]. However, no differences were found in sleep quality as measured by the Pittsburgh Sleep Quality Index (PSQI). This may suggest that 6 months post mTBI, youth and young adults may be less likely than matched OI or controls to meet PA guidelines at the 6-month post-injury timepoint. In a similar study demographic examining PA, fatigue, and sleep 6-18 months after mTBI, not meeting PA guidelines post-mTBI was associated with higher ratings of fatigue, but not motivation or concentration [98]. Examining youth (ages 5-18) with and without recurrent concussion, those without recurrent concussion history more frequently return to normal PA levels within 1-year (98% vs 85%; difference = 13% [95% CI 4-28]; $P < .0001$) [99]. These findings may suggest PA routines are often disrupted for periods longer than the acute recovery period after concussion [up to two weeks for adults and four weeks for children and adolescents [15]], and for those with multiple concussion histories this disruption may be greater. However, while examining disablement [defined in the study as increased concussion-related symptoms and lower health-related quality of life (HRQoL)] at the time of return to play (RTP), McGuine et al. (2019) found long-term disablement at 3, 6, and 12 months after SRC was not present when compared to baseline evaluation assessment in the pre-season and/or pre-injury setting [100]. These findings may suggest the opposite of other research discussed within this sub-section, though the research question focused on long-term disablement which may draw light to a limitation of the findings in the context of this literature review as disablement does not equate to augmented PA behaviours and does not speculate on other outcomes such as adiposity. While the findings by McGuine et al. (2019) were focused on symptom reporting and HRQoL which plausibly could affect behaviours such as PA, they did not include a specific subjective (like GPAQ) or objective outcome measure (like accelerometry or actigraphy) for PA. In another study evaluating the long-term outcomes following mTBI in adults, 47.3% of actively employed participants had not returned to work and staggering 67% of participants that previously participated in sports reported decreases in these sporting activities [101]. These findings in an adult population suggest that a large proportion of individuals suffer a massive disruption to their PA and working behaviours (which may involve forms of PA or manual labour) after mTBI, however, more research needs to be done to understand the strength of this relationship and its potential correlates.

In a cross-sectional study, Mercier et al. (2021) sought to examine both PA and sedentary behaviour and their potential association(s) with symptomology and quality of life (QoL) outcomes in adults (ages 18-65) with persistent post-concussion symptoms (PPCS) [102]. The main findings of the study were substantial as 85% of participants reported meeting CSEP PA guidelines (150-minutes/week of MVPA) before injury and a mere 28% of participants met these guidelines post-injury. Mean follow-up time was not included and was discussed along with lack of assessments across multiple time points as a limitation of the study, however inclusion criteria for PPCS required symptom presentation >5 months post-injury, up to 5-years [102]. Other notable findings of this study included that those who did meet PA guidelines post injury reported higher QoL and improved scores on measures regarding the functional impact of headache, fatigue, depression, and anxiety symptoms when compared to those not meeting guidelines. While this study focused specifically on those with PPCS, Mercier et al.'s (2021) findings suggest there is a risk for reduced PA behaviours and augmented sedentary behaviours due to concussion with more persistent symptoms. These PA outcomes were however measured with the Godin Leisure-Time Physical Exercise Questionnaire (GLTEQ), which is a subjective self-reported measure of PA in adult populations [103], potentially denoting a study limitation. Mercier et al.'s (2021) study examining PA behaviors, or its correlates demonstrates that work with objective measures of PA, such as actigraphy, is warranted in previously concussion-injured and/or PPCS-experiencing populations.

The literature discussed in this sub-section explored the link between concussion and PA through utilizing indirect and subjective measures such as self-reported surveys, potential correlates to sedentary behaviour like symptoms of fatigue, and the psychological and psychosocial impact of concussion on the injured and parents of the injured. While self-reported subjective measures may be cost and time-effective when compared to objectively recorded PA behaviours, in the context of concussion or mTBI there may be a large margin left for error when expecting previously concussed populations to recall accurate information, bias research may be subject to even when not examining a vulnerable population. There is limited literature exploring direct measures of PA beyond 3-5 day or acute (<30 days) settings and no literature examining specifically long-term PA (greater than 1year post-injury) using direct outcome measures were identified. This lack of objective outcome measure inquiry suggests there is a need for further research investigating the long-term consequences of SRC, and in the context of this literature review, precisely consequences related to changes in PA levels utilizing objective outcome measures that may limit recall or social desirability bias. Objective measurement devices such as tri-axial linear accelerometers, to be discussed shortly, that record movement and movement intensities may prove useful in mitigating these biases.

2.5.3 Psychosocial Factors Influencing Physical Activity After Concussion

There is evidence to suggest that fear of recurrent concussion and injury in individuals who have already sustained concussion is associated with higher vestibular and ocular symptoms that fall above clinical cut-off points at return-to-play time points in high school athletes [104]. These findings suggest there are psychological factors associated with experiencing a concussion which may influence symptom presentation and may also negatively impact subsequent PA participation. Factors such as social support from athletes, parents, and teammates have also been identified to influence recovery trajectories in youth athletes, where discrepancies between support attained and support desired in concussed individuals were identified [105]. This may suggest that, in the context of the impact concussion history may have on long-term PA levels, there are extrinsic risk factors for recovery trajectory and subsequently future PA participation.

PA levels may be altered by withdrawal from sport-participation or changes to PA behaviours as an indirect effect of concussion. It is plausible that athletes who have sustained an injury in collision sports may recuse themselves from further involvement and seek non-collision sport alternatives, to reduce their risk of future injury while maintaining benefits of aerobic health. In a study examining parents perceived requirements for informed removal of their child from American football sport participation, it was found over three-quarters of parents would choose to remove their child from play after sustaining multiple concussions, with nearly half of the parents making the same decision after two concussions [30]. These findings suggest there may be a decrease in sport-participation and subsequently PA may result from parental or familial influence. Additionally, systematic review has alluded to there being a lack of objective evidence for removal of sport based on prior concussions [106], which means participation removal is not yet standardized amongst individuals with concussion history. While it is understandable for a parent or guardian to decide to remove their child from high-risk or perceived high-risk sport participation, there are larger implications for child health if this PA is not replaced with other activities that can benefit the cardiovascular system. Regarding self-reported perceptions post-injury, youth (ages 16-18) in a 1-year mTBI follow-up study reported lower levels of interest in all categories of an interest checklist, where a decrease was found between follow-up and baseline for interest in physical activities [31]. These findings may suggest post-concussion changes in self-efficacy, the belief of an individual in their capabilities to organize and execute courses of action required to perform a given behaviour [32]. In a study looking to examine children's self-efficacy related to PA performance after mTBI, children with mTBI injury history demonstrated a decrease in activity-related self-efficacy when compared to a control group at the 12-week post-injury mark despite no group differences at the initial assessment [32]. Further to this, adolescence represents a key training window related to athletic development [107], which may have negative implications for PA participation later in life should it be interrupted. It is here that sports participation fosters athletic performance skills and influences physical and emotional well-being through improvements in self-efficacy and self-esteem [107]. Through sports participation we see a reduction in lifestyle diseases [107] and the effects of non-participation in sports as a result of previous injury may be significant to lifestyle and long-term health outcomes.

There is sufficient evidence to believe that sports injury may result in a psychological- or social-driven change to PA behaviours. This creates plausibility in injury or SRC injury experienced during adolescence changing or influencing PA behaviours both immediately and potentially later in life. Thus, further demonstrating the need to examine long-term PA behaviours in adults who sustained SRC during adolescent sport involvement.

2.6 Musculoskeletal Injury and Adolescent Sport Participation

While concussion is a substantial injury, it is only one form of injury that may be sustained during participation in sport. Musculoskeletal injuries (MSK) have been identified to be the most common sport-related injuries [108-110]. MSK injury itself is characterized by trauma and/or damage to muscle, bone, and/or joint tissue [111]. As per the International Olympic Committee Consensus Statement on the Methods for Recording and Reporting of Epidemiological Data on Injury and Illness in Sport, MSK mechanisms of injury may include either traumatic sudden-onset or gradual onset [13]. Black et al., (2021) surveyed 2029 Canadian adolescents (14-19 years of age) and report that the most common injury locations were the ankle (18.52%), head and face (18.14%), and knee (16.09%). The most frequently reported serious injury types were joint/ligament sprain (18.14%), fracture (17.50%), followed by concussion (13.67%) [9]. The top three sports by participation rates these 14-19 year old high school students, amongst 60 listed sport and recreation activities were as follows for males [basketball at 33.08% (95%CI: 27.67%, 39.00%), ice hockey at 20.46% (95%CI: 14.87, 27.47%), and soccer at 19.42% (95%CI: 15.67%, 23.80%)] and females [dance at 22.52% (95%CI: 17.98%, 27.82%), basketball at 18.32% (95%CI: 14.32%, 23.14%), and badminton at 17.84% (95%CI: 13.35%, 23.43%)] [9].

Like sport-related concussion, MSK injury may also remove individuals from sport participation in the acute setting post-injury, with this interruption to PA behaviours only being transient should the individual recover. It is plausible that MSK injury may result in similar psychological or psychosocial detriments as concussion injury with regards to sport-participation, where in post-concussion settings athlete interest in PA behaviours or parent perceptions of sport-participation may result in withdrawal [30, 31]. This notion was demonstrated in a study examining adolescents that sustained significant knee injury [anterior cruciate ligament (ACL) reconstruction], where it was identified that *'fear of re-injury'* and *'lack of confidence'* were the most common reasons for athletes failing to return to previous sport(s) participation after surgery [112]. Further, it was identified that PA levels via sport participation and psycho-social factors were potential determinants for an athlete's return to sport, where psychological profiling and post-operative psychological rehabilitation were suggested to be important considerations to help facilitate a return to sport. [112]. In conjunction with fear of re-injury, lack of confidence, and psycho-social factors surrounding injury, emotional trauma and prolonged impact on ability and willingness to engage in sport has been identified as a sequalae of MSK injury [12, 112, 113]. These findings suggest there are significant psychological determinants in returning to sport and re-engaging in PA behaviours after substantial injury and that there it may be crucial to identify who may need psychological rehabilitation post-injury to help facilitate more ideal PA and health related outcomes.

2.6.1 Long-Term Sequalae of Musculoskeletal Injury

The section above discussed how sport participation and PA behaviours may be negatively impacted by MSK injury and did not speculate on the pervasiveness of these participation or behavioural changes. In Toomey et al.'s (2022) study examining actigraph-measured levels of PA 3-12 years post-sport-related knee injury in adults aged 18-35, those with a history of knee injury had lower levels of MVPA [-13.5 minutes/day (95% CI -25.6, -1.4)] when compared to healthy controls with similar age, sex, and sport characteristics [29]. This objective measurement of PA behaviours is paramount as it made it possible to understand and quantify how those with significant MSK injury history performed with regards to daily MVPA levels to matched healthy controls. Ardern et al. (2012) examined 'medium-term' (defined as 2-7 year) return-to-sport outcomes after ACL reconstruction surgery, where less than 50% of their 314 participants (mean age 32.5) returned to playing sport at pre-injury levels [114]. However, level of play for participants was not speculated on in Ardern et al.'s (2012) study, which may characterize a limitation where level of play may augment or dictate whether or how quickly an individual returns to play as it may influence an injured athletes eagerness to return to sport, given competitive nature(s) of high-level play, as well as facilitate access to medical and rehabilitation-related services. Thus, it seems relevant in the context of exploring association(s) between concussion and changes to PA behaviours or adiposity that those with a history of MSK injury be used as a reference or comparative group as MSK injury has already been shown to affect long-term (≥5 year) objectively measured PA behaviours and adiposity measures [29, 36]. In the context of returning to play after injury, other objective measures such as lean mass index might be another important consideration as they may shed light on whether an individual has returned to the same level or intensity of activity or play.

As evidence already exists and as discussed above, one might expect lower levels of positive PA behaviours in individuals with long-term (≥5 year) MSK injury history relative to those without these injury histories. Well-established evidence regarding long-term MSK injury history sequelae further implores that long-term MSK injury history be a pertinent comparison group to those with long-term SRC injury history where thorough objectively measured outcomes from well-designed research is lacking. Further literature from these authors will be discussed as well shortly within sections pertaining to adiposity outcome measures.

2.7 Accelerometers and Actigraphy

Accelerometers have become some of the most common measures for tracking and examining movement and physiologic responses to PA [115]. Their ability to provide an objective measure of PA behaviors in both observed and free-living conditions allows them to be valuable tools when examining activity behaviours in a variety of contexts. Accelerometers track and record linear acceleration, an aspect of movement that may be analyzed to predict PA outcomes. As tri-axial and solid-state accelerometers [116, 117], ActiGraph activity monitors (ActiGraph, LLC) can differentiate between sedentary and PA behaviours and are validated for use in pediatric and adult populations [115, 118].

ActiGraphs are wearable accelerometers that provide an array of information about movement during wear time. ActiGraphs have been used in previous literature examining PA in individuals with a 3–12-year history of sport-related knee injury where previously injured youth and young adults had lower levels of MVPA when compared to uninjured controls [29]. The counts per minute (CPM) data they provide allow for movement to be classified into intensity domains [i.e., sedentary, light, moderate, vigorous, or MVPA] via cut-point algorithms. ActiGraph use has been validated in previous studies for adult populations [116, 119] and adults in free-living conditions [120]. ActiGraphs have also been validated in previous studies for use in youth populations [121-123]. However, the algorithm used to define cut-points may produce large variations in how movement is classified, thus potentially preventing the use of the same algorithm for both youth and adult populations [119, 124]. Variation in analysis of the same data with different algorithms has also produced large variation in how movement is classified [125, 126]. Two algorithms common to literature and provided by ActiGraph in their ActiLife v6.13.4 (2009-2015 Actigraph LLC) software that may be distinguished by their unique cut-points in adult populations are the Troiano (2008) and Freedson VM3 (2011) algorithms. Troiano cut-points were designed to capture activity intensities in adults based on track-walking data [124]. As one of the oldest and most common algorithms for adult populations, the Freedson VM3 [119] algorithm was an update for contemporary accelerometers based on treadmill-derived MET cut-points from the original 1998 algorithm (12). As previously stated, the cut-points employed by an algorithm such as an actigraph may differ algorithm to algorithm as well as device to device, while being used to collect movement data specific to different populations and ages [119, 120]. The PA bins that a selected algorithm will quantify movement within should ideally be comparable to the PA intensity as described in exercise physiology literature that is appropriate to a population and age-range, otherwise, there may be significant misclassification.

Within exercise physiology literature, it is standard to classify intensity according to one's rating of perceived exertion and/or via heart rate metrics [127]. While issues exist surrounding the calculation of one's maximal heart rate, estimated heart rate reserve [HRR (220 – age / resting heart rate)] has demonstrated greater utility than heart rate itself, as it considers age and resting heart rate when calculating relative exercise intensity [128]. Other HRR calculations may include

[220 – age], the most common and widely used maximum heart rate formula; [207 – 0.7 × age], the more precise formula adjusted for people over the age of 40; and [211 – 0.64 × age], the slightly more precise formula that adjusts for generally active people. HRR estimates allow for relative aerobic fitness to be reflected within a cardiorespiratory measure as lower resting heart rates associated with higher aerobic fitness will produce a higher HRRs. Nonetheless, various HRR threshold guidelines have been proposed throughout the literature from various organizations [e.g., Canadian Society for Exercise Physiology (CSEP) [129], American Congress of Rehabilitation Medicine (ACRM) [130] and MET guidelines [79]]. HRR thresholds for these guidelines are defined as: 1) CSEP: light (20-40% HRR), moderate (40-60%), and vigorous (60-85%) (15); 2) ACSM: light (20-40% HRR), moderate (40-60%), and vigorous (60-90%) [129]; and 3) MET: light (35-50% HRR), moderate (50-70%), and vigorous (70-85%) [79].

The use of ActiGraphs is present in the existing body of literature, however in the context of concussion or SRC, their use is largely focused on pre-injury baseline, 3–5-day post-SRC injury, or acute (<30 days) post-concussion settings. For example, Majerske et al. (2008) used actigraphy to monitor PA levels in high school athletes both before and after concussion. This study found those who sustained concussion had significantly reduced PA levels the first few days after injury when compared to pre-injury activity levels [131]. While this sheds light on plausible reductions in PA post-concussion injury while using objective measures, there is an apparent paucity of literature examining long-term, or *later-in-life*, [≥5 year [45]] objective measures of PA in those with a history of concussion [131]. If a relationship between concussion injury history and changes to long-term PA behaviours exist, it is imperative they be identified as PA and adiposity have been extensively studied in children, adolescents, adults, and older adults showing that higher levels of PA and lower levels of sedentary behaviour are associated with lower adiposity [132-140]. Given the context of this literature review, ActiGraphs appear to be a feasible method for acquiring and quantifying PA behaviours in the long-term post-concussion injury setting in adult populations.

2.8 Body Composition

Adiposity refers to the amount of body fat or adipose tissue an individual has. It is common to measure and acquire information related to adiposity through means such as calculated body mass index (BMI), waist circumference, or body composition analysis through various screening or scanning devices. BMI is a relatively common indirect measure of adiposity due to it only requiring height and weight as anthropometric measures to calculate [BMI = mass (kilograms)/height (meters)^2]. However, BMI has limitations as it does not account for specific tissue types (lean mass versus fat mass), and the underlying assumption of the measure is that a higher value is associated with a higher adiposity at a given height [141-143]. Consequently, previous research has demonstrated unreliability of the measure at values lower than 30kg/m^2 (the threshold value for obesity) [144], inability of BMI to assess fat distribution [142], and other methods such as DXA have been identified to provide valid and reliable direct estimates of spatially specific adiposity [145, 146].

Previous research has demonstrated that increases in adiposity are associated with increased risk of adverse health outcomes such as cardiovascular disease, diabetes, metabolic disease, some forms of cancer, and musculoskeletal disorder/disease [33-35]. Additionally, excess adipose tissue may lead to low-grade chronic inflammation, insulin resistance, and hormonal imbalances [35]. Higher amounts of adiposity may also be concomitant with decreased cardiovascular fitness, muscular strength, and mobility [33, 35]. Lastly, adiposity can also affect psychological health, body image, and self-esteem, which may lead to mental health concerns such as anxiety or depression [34].

In a 2004 analytic review seeking to estimate direct and indirect costs of physical inactivity and obesity in Canada in 2001, with relative risks associated with inactivity and obesity being determined from a meta-analysis of existing prospective studies, estimates were derived for both direct and indirect health care costs [37]. While costs included the prospective value of economic loss related to illness, injury-related disability, and premature death, the economic burden of physical inactivity in Canada was $5.3 billion and $4.3 billion for obesity [37]. Thus, the well-established consequences of excessive adiposity on physical, psychological, and economic well-being create an importance in examining what factors such as injury or concussion history may play a role in its development. In the context of this literature review, it is imperative that further inquiry into the effects of adolescent concussion on adiposity in adults later-in-life be examined and established.

Although BMI is an inexpensive and accessible way to index body mass by height, it has pronounced limitations in that it does not discriminate between fat mass or fat-free mass (also recognized as lean mass) [147, 148]. Addressing this, research has demonstrated that fat-free mass index (FFMI), also recognized as lean mass index [LMI (lean mass in kilograms/height^2)], is a valuable metric for assessing fat-free mass in athletes as it allows for assessing muscular development associated with PA behaviours that athletes participate in [149]. Both fat mass index [FMI (fat mass in kilograms/height^2)], describing fat-specific mass indexed by height, and LMI have previously been used to determine reference values for fat-free and fat mass in apparently healthy North American Caucasian groups across different age groups and sexes [150]. Here, ethnicity and racial differences in central adiposity and visceral adipose tissue (VAT), diabetes prevalence related to body composition, and distribution of fat mass have been previously identified in both youth and adult populations, thus potentially warranting racial/ethnic stratification and inquiry [151-155]. Additionally, adiposity-related risk factors have been identified to be racially and ethnically diverse in children, adolescents, and adults [153, 156]. For reference, typical LMI values for 18- to 34-year-old North American Caucasian subjects at the 50th percentile was found to be 18.9 kg/m^2 (95% CI: 16.8 – 21.1 kg/m^2) for males and 14.7 kg/m^2 (95% CI: 13.8 – 17.6 kg/m^2) for females, denoting approximately 20% lower LMI for females relative to males in this young adult age range [150]. When examining fat mass in the same population at the 50th percentile, an FMI of 4.0 kg/m^2 (95% CI: 2.2 – 7.0 kg/m^2) was identified for males and 5.5 kg/m^2 (95% CI: 3.5 – 8.7 kg/m^2) for females in the 18- to 34-year-old age range [150]. The differences observed here in FMI and LMI between men and women may be attributed to a number of factors including hormonal influences and metabolic differences, where previous research has also shown that women generally have a higher prevalence of obesity relative to men [147, 148, 157]. In conjunction with this, higher FMI may be associated with worse vascular health that is not improved by increases in LMI [158]. With regards to the protective effect of PA participation, research examining student athletes has demonstrated that there is higher prevalence of obesity in non-athletic populations [159, 160].

Overall, both LMI and FMI appear to be relevant metrics to be used when examining body composition due to their implications towards somatic health, independent from each other. As such, they may prove to be valuable outcome measures when examining body composition in adults with long-term injury history where the relationship between injury history and changes to PA behaviours are being examined.

2.8.1 Dual Energy X-ray Absorptiometry

Dual-energy X-ray absorptiometry (DXA) scanners are medical imaging devices typically used to measure body composition [161]. Here, body composition is quantified amounts of lean tissue and fat tissue, while also collecting bone mineral density (BMD) [161]. DXA scanners work through the emission of two energy levels of X-rays that are typically at 70 and 140 kilovolts (kV) that pass through the body, being absorbed by different tissues at varying degrees [161]. The scanner then measures the amount of X-rays absorbed which allows for determination of the composition of different body tissues [161].

DXA is a common clinical method of acquiring body fat percentage and lean tissue mass measures, with short-term reproducibility showing small precision error [162]. For body composition studies, DXA displays the advantages of requiring only 10-20 minutes for administration, with minimal radiation dose, giving regional as well as total-body values [162]. When examining appendicular lean soft tissue and total body skeletal muscle using magnetic resonance imaging (MRI) and DXA, DXA was identified as capable of providing reliable and accurate estimates of total body skeletal mass in a sample of adult men and women when compared to MRI [163]. While MRI may be considered the gold standard for body composition analysis and imaging, DXA has also been validated against other methods such as underwater weighing [164]. This is important as DXA imaging costs substantially less money than MRI imaging, while requiring less specialized equipment. DXA has previously been used to examine percent fat mass, percent fat-free mass, trunk fat mass, and bone mineral density in youth [165] as well as adult [36] populations. DXA FMI values by sex, matched to WHO BMI classifications for Americans using data from the National Health and Nutrition Examining Survey (NHANES) are as follows: males [severe fat defecit (<2), moderate fat defecit (2 – <2.3), mild fat deficit (2.3 – <3), normal (3 – 6), excess fat (>6 – 9), obese class 1 (>9 – 12), obese class 2 (>12 – 15), obese class 3 (>15)], females [severe fat defecit (<3.5), moderate fat defecit (3.5 – <4), mild fat deficit (4 – <5), normal (5 – 9), excess fat (>9 – 13), obese class 1 (>13 – 17), obese class 2 (>17 – 21), obese class 3 (>3)] [166]. DXA LMI values [age in years (median ± SD)] by sex and age, matched to WHO BMI classifications for white Americans using data from NHANES are as follows: males [20 (18.98±2.50), 25 (19.31±2.52), 30 (19.60±2.54), 35 (19.85±2.56)], females [20 (15.60±2.01), 25 (15.83±2.10), 30 (16.03±2.18), 35 (16.19±2.26)] [166]. LMI did not confound reference range FMI values and LMI values were stratified by ethnicity (white, black, Mexican American), and as such the above values are a typical value for reference for Caucasian demographics [166]. In summary, DXA appears to provide reliable estimates of body composition metrics in clinical populations of children and adults and reference, providing value in DXA use in a study examining adiposity outcomes in any context, and values are available that describe FMI ranges by sex as well as typical LMI values by sex and ethnicity.

2.8.2 Body Composition and Injury History

There is limited literature examining long-term (≥5 year) body composition after injury sustained in youth. However, in a study examining body composition in young adults and adolescents (15-26 years of age) with a history of knee injury (median follow-up time 6.9 years) in youth sport, Toomey et al. (2017) found that when compared to matched uninjured controls, injured individuals had a higher BMI of 1.79 (range: 0.94 - 2.63), fat mass of 2.3% (range: 0.97 - 3.63), and fat mass index (FMI; kg/m^2) of 1.05 (range: 0.53 - 1.57). Here, using the Godin Leisure-Time Exercise Questionnaire (GLTEQ) injured participants also reported slightly less, though non-significant, time spent in weekly total PA [36]. Jespersen et al., (2014) identified total body fat and BMI to potentially increase the risk of lower-body injury in Danish children (7-12 years of age).

While this directionality is the inverse of the relationship relevant to the context of this literature review, it does potentially highlight a confounding factor of pre-existing adiposity to injury as a potential correlate to both injury risk and as a result long-term health outcomes [167]. Toomey et al.'s (2017) paper suggests that in the context of MSK injury history BMI, fat mass, and FMI increase when compared to healthy matched uninjured controls [36]. Thus, there is sufficient evidence for MSK injury history to affect measures of adiposity in long-term (≥5 years) injury settings. This further supports that MSK injury is a fundamental comparator or reference group when examining long-term concussion history as one might expect to see changes to both PA behaviours, as discussed in previous sections, and now adiposity measures.

2.9 Non-Modifiable Risk Factors and Concussion

It is plausible to hypothesize that any factors that may influence the risk of concussion, concussion presentation, or concussion recovery trajectory may also be associated with long-term PA participation in individuals with a history of concussion. This is possible as symptom presentation could influence likelihood of access to health care resources affecting recovery trajectory and recovery trajectory could influence returning to or lack of returning to pre-existing PA behaviours. Risk-modifying factors have also been identified as important considerations that should be included in well-designed cohort studies when examining the long-term effects of concussion as discussed in reviews around surrounding the 6th International Consensus Conference on Concussion in Sport [45]. Narrowing these broad statements down to factors explored in existing literature, where sex, age, and pre-existing comorbidities have all been shown to influence the presentation of clinical symptoms associated with concussion as well as functional deficit(s) following concussion [168]. Males typically report lower symptoms than females at baseline as well as following concussion [169-171], with symptom reporting also increasing for those with history of concussion [169, 171, 172], attention-deficit/hyperactivity disorder (ADHD) [173, 174], psychiatric conditions like anxiety or depression [173], sleep disorder [175], lower levels of aerobic fitness [176], and for individuals playing collision compared to non-collision sport(s) [173]. Iverson et al. (2015) also identified attention-deficit hyperactivity disorder (ADHD), learning disability (i.e., dyslexia), psychiatric conditions (i.e., anxiety, depression), migraine/headache disorder, and previous concussion history to have a positive association with pre-injury symptoms. This indicates these factors or covariates augment symptom presentation in both the presence and absence of concussion. While no clear association was identified in this literature review between concussion-like symptom presentation and PA behaviours independently, in the context of association between concussion history and PA behaviours it may be important to consider factors such as sex, age, and pre-existing comorbidities shown to influence clinical symptoms as well as functional deficits following concussion.

2.10 Time Since and Time Loss After Injury

While examining the long-term effects of concussion and/or MSK injury on PA behaviours, time-since injury may be a plausible correlate to changes in PA behaviours as this may reflect an individual's ability to recover from previous injury. The physiological process of healing damaged tissue involves the immune, molecular, and cellular biological systems of the body [177]. Healing may also be influenced by a variety of factors such as the age of an individual [178] and the severity of tissue damage [177] where increased age and severity of tissue damage inhibits healing. Thus, in context of examining long-term PA levels after MSK or SRC injury, age at time of injury as well as severity of injury sustained are important factors to consider.

The reality that healing may be affected by age and age may reflect time since injury when isolating for injury sustained in adolescence, suggests that age may be an important factor to consider when examining long-term injury history. The severity of tissue damage may however be a difficult factor to consider when examining populations with a variety of MSK injury histories. Despite this, in the context of ACL injury, Ardern et al. (2012) identified a relationship between injury severity and time loss from sport. Considering time loss from sport reflects at least a transient change in PA behaviours, this highlights the necessity for both injury severity and time loss from injury to be considered in the context of long-term PA levels after MSK or SRC injury. Injury severity may also be operationally defined by subsequent time-loss from sport in some sports medicine literature [179] and based on criteria describing sport injury severity, sporting and working time loss as a result of injury are considered among the most relevant [180]. What this suggests is that time loss from sport as a result of injury is an important consideration when examining the associations between injury history and PA behaviours, and it may shed light on the role injury severity plays in long-term PA behaviours after injury. This is particularly important when considering a historical cohort design where injury severity may be difficult to ascertain or effectively quantify due to the amount of time since injury conceivably introducing a variable amount of recall bias. Time since injury may also plausibly reflect the potential for recovery after injury as time for tissue healing, rehabilitation if necessary, and inherently recovery as whole is physiologically dependent. However, there are limitations to how time since injury may be examined analytically in the context of multiple injury history that a long-term (≥5 years since initial injury) cohort study may account for.

In summary, time loss from injury and time since injury are important correlates that should be accounted for when examining relationships between injury sustained in youth and PA behaviours in adults. Examination into injury history and how best to account for this may be warranted to effectively adjust for this potential covariate to SRC injury history and later-in-life PA behaviours.

2.11 Limitations and Future Directions

Firstly, the CISG has recently identified a paucity of research examining the later-in-life (≥5 years since injury) sequalae of SRC in a review [45] for the most recent Consensus Statement on Concussion in Sport [15]. This has drawn light to this being a much-needed area for future research in the concussion field. Thus, much of the literature described in this chapter involved individuals with concussion injury in the acute (≤30 day) setting, with no literature obtaining any measures for any health-related outcome in concussed populations specifically beyond the 2-year mark post-injury. Following this, much of the research described in the context of concussion only involved objective measures within the first month post-injury, with only subjective measures extending to that 2-year mark. Thus, with PA behaviours and adiposity in mind, there is no research quantifying either in either long-term or later-in-life settings.

As this literature review focused on aspects of concussion, PA behaviour, or adiposity independently, how they might relate to each other, or lastly in reference to literature examining MSK injury, there is no way to accurately speculate on the ways in which cofactors such as sex, age, social constructs of gender, or other important cofactors that could impact long-term SRC sequalae. With respect to gender itself, this may be that despite a steadily increasing number of individuals reporting as transgender there is a gross underrepresentation of transgender individuals in medical research [181]. Knowledge of these co-factors in acute concussion settings or the impacts they have on PA behaviours or adiposity were discussed briefly within respective subsections as it might be expected to see some of these highlighted differences in the context of long-term SRC history.

2.12 Conclusion

There is an apparent need to examine long-term PA behaviour and adiposity outcomes in adults who have sustained adolescent SRC. Literature and associations discussed in this chapter were done so to discuss the importance of PA behaviours and adiposity outcomes with regards to health-related outcomes, as well as speculate on how these outcomes may be affected by adolescent SRC in adults. The findings from the chapters to follow will elaborate on methodology required to effectively examine these outcomes in concussed adult populations as well as serve to facilitate a better understanding of the long-term impacts of SRC. This understanding will hopefully inform improved management of SRC beyond the acute setting in ways that might help mitigate negative health outcomes later in life. This research will also serve to fill an apparent gap in existing literature examining sequalae after concussion and MSK injury experienced ≥5 years ago during the potentially neurodevelopmentally vulnerable period of adolescence.

Chapter 3. Validity of GT3X+ ActiGraph algorithms for physical activity intensities in young adults using a modified Buffalo Concussion Treadmill Test

3.1 Background

Concussions are an encumbering injury with the potential to affect the mental, financial, physical, and academic well-being of an athlete [55]. The long-term effects of concussion are poorly understood where a paucity exists regarding the investigation of objective measures of physical activity (PA) following sport-related concussion (SRC) [21, 182]. The Buffalo Concussion Treadmill test is an incremental exercise test designed from the Balke Cardiac test to examine symptom exacerbation following concussion [24, 26, 27, 183]. This may indicate it is an appropriate laboratory exercise test when examining ActiGraph algorithm-defined PA intensities in the context of concussion injury or concussion injury history [184]. Despite previous research demonstrating use of both Troiano [124] and Freedson VM3 [119] algorithms [185-187], the validity of ActiGraph GT3X+ algorithms in the context of concussion injury or concussion injury history in adults has not been established.

ActiGraphs (ActiGraph, LLC) are wearable accelerometers which provide an array of information about movement during wear time. Count per minute (CPM) data enable movement to be classified into intensity domains (i.e., sedentary, light, moderate, vigorous) via cut-point algorithms [116]. Actigraphy has been validated in previous studies for adult populations [116, 119, 120]. However, the employed algorithm and the associated cut-points defined by the algorithm may potentially induce variations in movement classifications [119, 124]. Furthermore, analysis of *the same data* with different algorithms can also produce different activity levels [125, 126, 184]. Two algorithms common within the broader literature for adult populations and provided by ActiGraph (ActiLife v6.13.4 software: 2009-2015 Actigraph, LLC) are the Troiano [124] and Freedson [119] algorithms. Troiano cut-points were designed to capture activity intensities in adults based on track-walking data [124], thus potentially indicating it's limitation in capturing incline-dependent intensification of PA. As one of the oldest and more common algorithms, the Freedson VM3 [119] algorithm was an update for contemporary accelerometers based off treadmill-derived metabolic equivalent task (MET) cut-points from the original 1998 algorithm [188].

In addition to actigraphy, classification of exercise intensity is often assessed through rating of perceived exercise (RPE) intensity and/or via heart rate metrics [127]. As heart rate ranges are variable, heart rate reserve (HRR) is often utilized as it considers age and resting heart rate when calculating relative exercise intensity [128]. Various HRR threshold guidelines have been proposed [e.g., Canadian Society for Exercise Physiology (CSEP) [129], American College of Sports Medicine (ACSM) [130] and MET guidelines [79]]. While numerous actigraph algorithm cut-points and HRR threshold guidelines exist, it is unknown the extent that these values are correlated with one-another in adults under both free- and laboratory-based exercise conditions.

The purpose of this study was to identify which algorithm [Troiano [124] or Freedson VM3 [119]] more appropriately defines activity intensities by comparing ActiGraph-recorded PA at intensities categorized by each respective algorithm with HRR-defined PA intensity levels (i.e., CSEP, ACSM, and MET) during a controlled laboratory modified Buffalo Concussion Treadmill Test in young adults (ages 18-35). A secondary objective was to examine sex differences for activity intensities for both algorithms, despite ActiGraphs adjusting for sex, height, and weight during appropriate device initialization. Considering that PA intensities are incline-dependent during a BCTT, and the algorithms were designed for free-living use using flat track-walking data, it was hypothesized that both algorithms would overestimate MVPA.

3.2 Materials & Methods

3.2.1 Study Setting & Participants

This was a cross-sectional study with procedures and sample size informed by previous research validating algorithms in adolescent populations [184]. Participants were recruited via convenience sampling within the Sport Injury Prevention Research Centre and Human Performance Laboratory in the Faculty of Kinesiology, University of Calgary. Participants were free of cardiovascular, neurological, respiratory, and cerebrovascular disease and between the ages of 18 and 35 years. This age range was selected as it includes the age range of interest for the larger historical cohort study SHRed Consequences of Concussion [examining long-term health-related outcomes in young adults who sustained SRC 5-15 years ago, compared to individuals with a 5–15-year history of musculoskeletal injury, and health controls]. The results from this validation study will inform the cut-point algorithm selection for this larger study. Written informed consent was obtained from all participants, and all protocols adhered to the ethical protocol approved by the Conjoint Health and Research Ethics Board at the University of Calgary (REB 20-2112).

3.2.2 Procedures

Height (centimeters), weight (kilograms), date of birth, biological sex, and self-reported dominant hand information were acquired for accurate ActiGraph (GT3X+; ActiGraph LLC) initialization. Participants completed the testing protocol a minimum of one-hour following exercise, as autonomic recovery has shown to occur during this time frame [189]. To maximize the external validity and general application of the findings, daily factors influencing cardiac function were not strictly controlled [e.g., caffeine consumption [190], sleep levels [191, 192], time of day [193]]. This allowed the results to reflect the appropriate algorithm to be more readily applied to measurements collected within free-living settings. Initialized GT3X+ ActiGraph (ActiGraph LLC) units were worn above the anterior-superior iliac spine on the participants' dominant side for two minutes prior-to and throughout the duration of the modified BCTT [183, 184]. Participants were concurrently fitted with a chest-worn Polar heart rate monitor (T31C; Polar Electro) synced with a Polar Receiver Interface Cable (ADInstruments, Colorado Springs, CO, United States). Data were time-synced and sampled at 200-1000Hz using commercial software [194] (LabChart Pro Version 8, ADInstruments; PL3516 PowerLab 16/35, ADInstruments, Colorado Springs, CO, USA), and stored securely for offline analysis.

3.2.3 Buffalo Concussion Treadmill Test

Participants completed a sitting quiet-rest period (5-minutes) to obtain resting heart rate. Subsequently, a modified BCTT was administered based upon procedures previously used examining algorithm cut-points for post-concussion adolescents (ages 15-17 years) [184]. Using a treadmill (model T635M; SportsArt) the initial stage began at 1.6 mph (2.6 km/h) and increased each minute by 0.4 mph until a speed of 3.2 mph (5.1 km/h) was achieved. The addition of four one-minute stages prior to reaching 3.2mph was incorporated to capture a greater amount of light PA than might be achieved with a test starting at the originally designated speed (3.2mph). Once a speed of 3.2 mph was achieved, the incline was increased 1% per minute-stage until an incline of 15% was attained. Treadmill speed was then increased 0.2 mph (0.3 km/h) until test termination. The a-priori guidelines for test cessation consisted of: 1) volitional fatigue, 2) heart rate >180, or

3) RPE ≥18 (scale 6-20) [25, 183]. RPE was self-reported at the end of each BCTT stage. During the test, percent HRR was calculated using the following formula:

$$\%HRR = \frac{Measured\ HR}{(HRmax - age) - resting\ HR} * 100$$

3.2.4 Actigraphy & Movement Guidelines

ActiLife v6.13.4 (2009-2015 ActiGraph LLC) was used for ActiGraph wear-time (WT) validation and analysis. The Choi [195] wear-time algorithm was used for WT validation. As only observed active WT was included in analysis, WT validation algorithms would yield identical PA counts. ActiGraph count data were analyzed in 15-second epochs using both the Freedson VM3 and Troiano scoring algorithms [119, 124]. These algorithms were selected to be appropriate for use in 18–35-year-old adults when examining light, moderate, moderate-to-vigorous, and vigorous PA counts using ActiGraph GT3X+ models [119, 124, 196, 197]. Physiologically categorized exertional reference levels were included to reflect HRR guidelines from CSEP (15), ACSM (13), and MET framework (17). For CSEP, ACSM, and MET framework these were respectively 20-40%, 20-40%, and 35-50% for light, 40-60%, 40-60%, and 50-70% for moderate, and 60-85%, 60-90%, and 70-85% for vigorous intensities. Moderate-to-vigorous activity intensities were defined as inclusive of both moderate and vigorous thresholds for each set of guidelines.

3.2.5 Statistical Analysis

Descriptive statistics and statistical analyses were completed in STATA v18 [198]. Data normality was assessed visually as well as through Shapiro-Wilks normality tests. Multiple linear regression modeling of algorithm-defined time spent in each activity bin was completed to assess for sex differences. Bland Altman Limits of Agreement plots were generated to display 95% limits of agreement of for both Troiano and Freedson algorithm-defined minutes in each activity bin with HRR-defined guidelines. An a-priori alpha of 0.05 was used.

3.3 Results

Table 1 and Figure 1 display participant descriptive statistics and individual HRR responses to the modified BCTT, respectively. On average modified BCTT test durations in minutes (range) were 24.85 (18-28) for males and 21.70 (22-29) for females.

Table 2 displays mean minutes spent in each activity bin by sex for HRR-defined guidelines (CSEP, ACSM, MET) and both Troiano and Freedson algorithms. No differences were identified between CSEP and ACSM guidelines for minutes spent at any activity intensity. As such comparisons and limits of agreement were completed and displayed for ActiGraph algorithms relative to CSEP guidelines. Minutes spent at light intensity were lower for both algorithms when compared to CSEP guidelines, with mean differences (95%CI) of -5.49 (-6.79, -4.19) for Freedson males, -6.29 (-8.02, -4.56) for Freedson females, -5.76 (-7.25, -4.19) for Troiano males, and -4.99 (-6.19, -3.79) for Troiano females. Minutes spent at moderate intensities were higher for both algorithms when compared to CSEP guidelines, with mean differences (95%CI) of 7.48 (4.74, 10.22) for Freedson males, 9.70 (7.76, 11.65) for Freedson females, 8.80 (6.27, 11.33) for Troiano males, and 12.03 (10.37, 13.69) for Troiano females. Minutes spent at vigorous intensities were lower compared to CSEP guidelines only for Troiano females with a mean difference of -3.80 (95%CI: -6.26, -1.34). Minutes spent at MVPA intensities were higher for both algorithms when compared to CSEP guidelines, with mean differences (95%CI) of 10.69 (6.92, 14.45) for Freedson males, 7.83 (5.70, 9.97) for Freedson females, 10.16 (6.48, 13.84) for Troiano males, and 7.33 (5.41, 9.26) for Troiano females. Table 3 displays multiple linear regression results examining sex differences for minutes spent in each activity bin. For both algorithms, minutes spent in vigorous [Freedson: 5.08 (95%CI: 0.45, 9.70; p=0.03), Troiano: 6.05 (95%CI: 1.73, 10.37; p=0.01)] and MVPA [Freedson: 3.13 (95%CI: 0.51, 5.74; p=0.02), Troiano: 3.10 (95%CI: 0.44, 5.76; p=0.03)] for males relative to females were higher.

Figures 2 display Bland Altman 95% Limits of Agreement (LoA) for each activity intensity with HRR-defined CSEP guidelines. Table 4 summarizes mean differences for each algorithm at a given intensity with 95% lower and upper LoA with HRR-defined CSEP guidelines. Both Freedson and Troiano defined minutes spent in light activity were underestimated [Freedson: -5.59 (LoA: -1.73, -10.05), Troiano: -5.38 (LoA: -1.69, -9.06)]. Both Freedson and Troiano defined minutes spent in moderate activity were overestimated [Freedson: 8.59 (LoA: 1.85, 15.31), Troiano: 10.42 (LoA: 3.85, 16.98)]. Freedson and Troiano LoAs for vigorous activity agreement with CSEP guidelines were [Freedson: 1.14 (LoA: -10.90, 13.18), Troiano: -0.91 (LoA: -12.83, 11.04)]. Both Freedson and Troiano defined minutes spent in MVPA were overestimated [Freedson: 9.26 (LoA: 0.61, 17.91), Troiano: 8.75 (LoA: 0.42, 17.08)]. For for both algorithm-defined minutes spent in light, moderate, and vigorous activity a trend was observed in the Bland-Altman LoA plots where greater mean differences are observed at higher mean minutes (Figure 2). Identified sex-differences are also observed in the Bland-Altman LoA plots for vigorous and MVPA intensites with males having greater mean differences in minutes spent at these intensities.

3.4 Discussion and Limitations

The key finding from this study was that both algorithms appear to provide comparable estimates for minutes spent at each activity intensity for both males and females. However, they may do a poor job in capturing intensification of exercise dictated by inclination during walking movements, as captured with overall poor LoAs with HRR-defined CSEP guidelines. Secondly, sex-differences were identified at both vigorous and MVPA intensities, resulting in greater overestimation for males relative to females. As height, weight, and sex are important considerations in context of accurately measured movement behaviors using GT3X+ ActiGraphs and are required for appropriate device initialization, this was not expected. Consequently, cut-point algorithm selection and sex may be important considerations for clinical interpretation of ActiGraph findings using either the Troiano or Freedson algorithms in young adult populations.

Sex differences were observed, with males spending greater amounts of time in vigorous and MVPA intensities (Table 3 & Figure 2). Considering sex-differences would account for anthropometric variation (Table 1), we suspect changes to gait movements as a result of height and weight variation may explain these findings. Frontal plane pelvis and torso motion has been identified as discriminatory factors between female and male gait patterns [199], and as ActiGraph GT3X+ tri-axial accelerometers are waist-worn devices, it is plausible differences observed in our study are a result of biological sex-gait differences. Height has previously been shown to influence aspects of gait, including gait speed, stride length, and cadence [200, 201]. Therefore, height may affect peak accelerations and associated counts used to describe intensity of movement by ActiGraph devices. The significant findings of sex being associated with defined PA intensities during a BCTT is worth noting as ActiGraph devices already require this information to be initialized for each individual and are designed to adjust for it. However, this may suggest that these data may not be effectively adjusted for by the devices for this specific movement modality, where activity intensity was primarily defined by subtle changes to inclination. However, this does not speculate on why gross underestimation of light intensity occurred, as flat-walking movement speed started at 1.6mph (2.4kmh) and increased to 3.2mph over a four-minute period, where HRR values suggest most individuals should have remained at a light intensity classification (Figure 1).

Limitations of this study begin with the design of the two algorithms being validated. Both Troiano and Freedson algorithms were designed for capturing activity intensities in flat-walking environments [124, 188]. This suggests incline, the progressively increasing dimension of the modified-BCTT designed to increase intensity of the test [24], may not be effectively captured using these algorithms. Additionally, the modified-BCTT was administered in a controlled laboratory environment which is not the free-living environment these algorithms were designed for, limiting the external validity. Identifying and controlling for gait patterns were not included in this study's design and could potentially be an important factor to consider as gait patterns may help describe sex and height differences that were identified, while also improving internal validity.

The implications of this study are that both algorithms appear comparable when examining this specific modality of exercise and may also suggest they are comparable for estimating movement intensities. If these results from a modified-BCTT were to be used as a reference for free-living environments or a study of larger design, both algorithms are able to be used and potentially compared within the context of that study's design. Future research directions regarding validity of algorithms used to examine activity levels and intensities should likely be focused on multi-modal activities and/or include a range of activities, as well as identify where or when ActiGraph software fails to appropriately employ sex, height, and weight adjustments.

3.5 Conclusion

Sex appears to be an important consideration beyond the initialization of GT3X+ ActiGraph accelerometers. Both Troiano [124] and Freedson VM3 [119] algorithms underestimated light activity and overestimated both vigorous activity and MVPA compared to the HRR-defined CSEP guidelines. Both algorithms displayed similar limits of mean agreement with CSEP guidelines and appear equally appropriate for use in young adult populations for field-based measurements of physical activity.

3.6 Tables & Figures

Table 1

Descriptive statistics for all participants by biological sex (10 male, 10 female) that completed the modified Buffalo Concussion Treadmill Test protocol.

Descriptive Statisstic (n=20)	Mean	Range	Standard Deviation
Age (years)			
Male	25.6	21.1 - 35.0	4.3
Female	25.1	21.3 - 32.8	3.9
Height (centimeters)			
Male	178.3	163.0 - 190.5	10
Female	166	156.0 - 176.0	6.9
Weight (kilograms)			
Male	82.4	67.3 - 104.5	11.2
Female	65.7	57.7 - 77.0	6.5
Test Duration (minutes)			
Male	24.9	22.0 - 28.75	2.4
Female	21.7	18.0 - 27.75	3.7

Table 2

Mean Minutes Spent in Light, Moderate, Vigorous, and Moderate-to-Vigorous Activity Bins by Guideline and Sex

Intensity	Sex	CSEP	ACSM	MET	Troiano	Freedson
Light	Male	7.81 (2.36)	7.81 (2.36)	5.12 (0.86)	2.05 (0.73)	1.53 (1.02)
	Female	7.04 (1.81)	7.04 (1.81)	4.39 (0.64)	2.05 (0.71)	1.55 (0.86)
Moderate	Male	6.10 (1.50)	6.10 (1.50)	5.53 (1.55)	14.90 (4.52)	13.58 (4.81)
	Female	5.82 (1.35)	5.82 (1.35)	5.29 (1.78)	17.85 (2.98)	15.23 (3.50)
Vigorous	Male	6.24 (2.11)	6.68 (2.50)	3.62 (1.48)	8.08 (5.70)	9.93 (5.88)
	Female	6.24 (1.82)	6.62 (1.90)	3.73 (1.40)	2.03 (3.12)	4.85 (3.73)
MVPA	Male	12.82 (3.46)	12.82 (3.45)	9.62 (3.18)	22.98 (2.22)	23.50 (2.50)
	Female	12.54 (2.87)	12.54 (2.99)	9.49 (2.65)	19.88 (3.33)	20.38 (3.04)

**Defined guidelines [American College of Sports Medicine (ACSM), Canadian Society for Exercise Physiology (CSEP), or metabolic equivalent of task (MET)], stratified by sex (n=20; 10 male, 10 female).*

Table 3

Multiple Linear Regression for Male Relative to Female Minutes Spent in Each Activity Intensity for Troiano and Freedson Algorithms

Algorithm	Intensity	Beta	95%CI		p-value
Troiano					
	Light	0	-0.67626	0.676259	1.00
	Moderate	-2.95	-6.54688	0.646881	0.102
	Vigorous	6.05	1.732661	10.36734	0.009
	MVPA	3.1	0.44056	5.75944	0.025
Freedson					
	Light	-0.025	-0.91169	0.861691	0.953
	Moderate	-1.95	-5.90185	2.001853	0.314
	Vigorous	5.075	0.446709	9.703291	0.033
	MVPA	3.125	0.510252	5.739748	0.022

**Beta represents male relative to female change in minutes spent in each activity bin for each respective algorithm.*

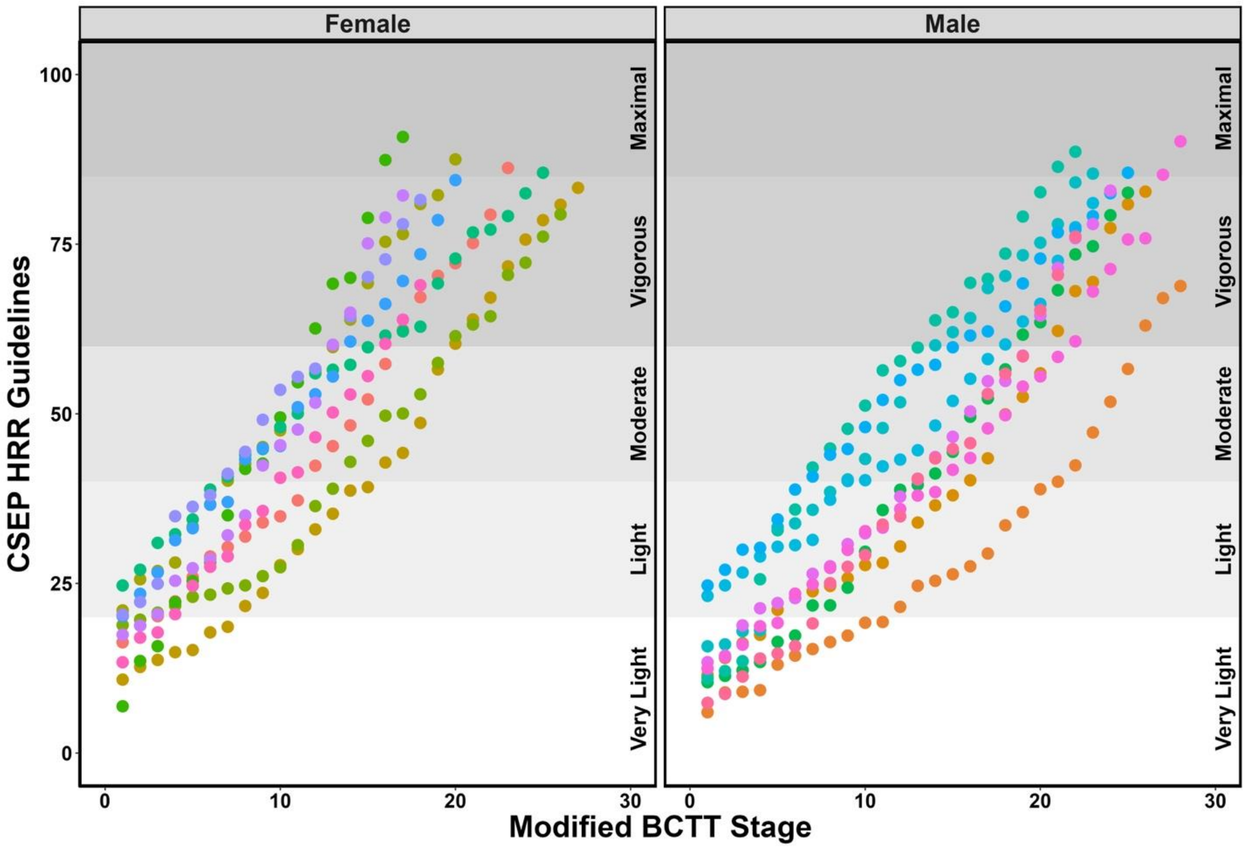
Table 4

Mean Differences and 95% Limits of Agreement (LoA) for Troiano and Freedson Algorithms with HRR-Defined CSEP Guidelines

Algorithm	Intensity	Difference	95% Lower LoA	95% Upper LoA
Freedson				
	Light	-5.89	-1.73	-10.05
	Moderate	8.59	1.88	15.31
	Vigorous	1.14	-10.90	13.18
	MVPA	9.26	0.61	17.91
Troiano				
	Light	-5.38	-1.69	-9.06
	Moderate	10.42	3.85	16.98
	Vigorous	-0.91	-12.86	11.04
	MVPA	8.75	0.42	17.08

Figure 1

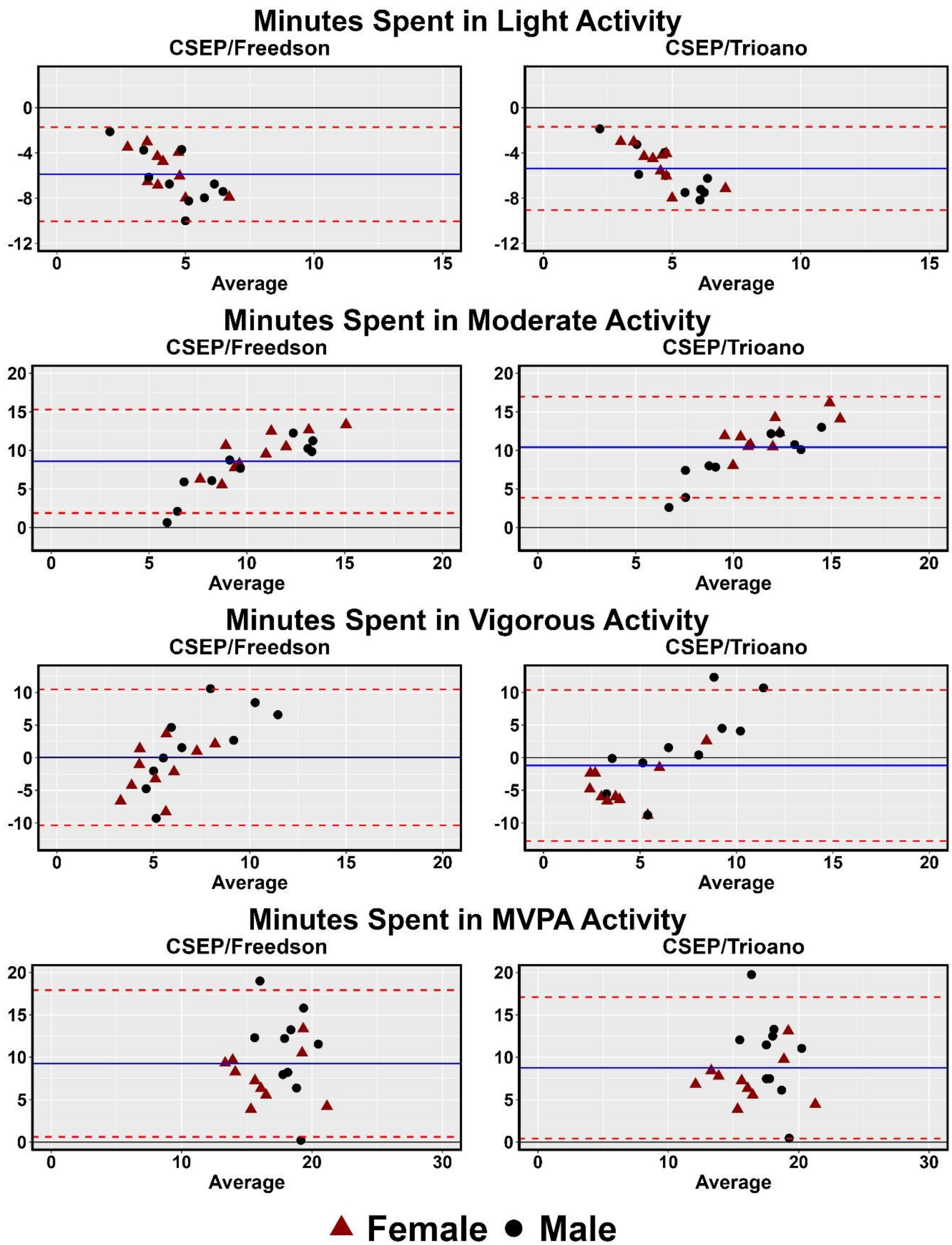
Individual Heart Rate Reserve Responses During the Modified Buffalo Concussion Treadmill Test



**Individual heart rate reserve (HRR) responses observed in males (n=10) and females (n=10) against the minute-stages of the modified Buffalo Concussion Treadmill Test (BCTT). Activity intensities (very light, light, moderate, vigorous, and maximal) were calculated and overlaid based on Canadian Society for Exercise Physiology (CSEP) guidelines.*

Figure 2

Bland Altman 95% Limits of Agreement for Each Movement Intensity by Sex with HRR-Defined CSEP Guidelines



Chapter 4. Consequences of sport-related concussion: Exploring long-term adiposity

4.1 Background

An estimated 3 million people sustain a concussion injury from sports or recreation activities in North America annually [53]. Fifty percent of these estimated 3 million North American injuries are sustained by children or adolescents [53]. Overall, it is estimated that 1 in 9 (11.1%) of Canadian youth experience a concussion every year, with risk increasing when participating in contact or collision sport(s) [9, 54]. Furthermore, a concussion can potentially be a debilitating injury affecting the physical, mental, financial, and academic well-being of an individual, as well as their family and friends [55]. As defined in the Consensus statement on concussion in sport: the 6th International Conference on Concussion in Sport – Amsterdam October 2022 - a sport-related concussion (SRC) as "a transient disruption in neurological function induced by biomechanical forces transmitted to the brain by either a direct or indirect blow to the head or body" [15]. In a systematic review informing this Consensus, a call was made for a multifaceted research and funding to develop a greater understanding of long-term athlete health after concussion [15, 45]. Long-term defined as equal to or greater than a 5-year concussion history [45].

Previous research suggests that fear of recurrent concussion and injury in individuals who have previous concussion history [104], parental removal from sport [30], as well as level of support obtained during recovery [105] may be psychosocial determinants influencing whether adolescents continue to participate in sport-related activities. Thus, it may be plausible to suggest that concussion may influence long-term participation in sport and subsequently physical activity levels in individuals with concussion injury history. Physical activity has been shown to influence adipose tissues at the cellular level, including having beneficial effects on inflammation and metabolic function, improved tissue insulin sensitivity, and overall reductions of body fat levels [202-205]. A systematic review focusing on the effect(s) of physical activity on weight loss suggests that it is a crucial behavioral correlate to successful weight loss and healthy-weight management through reductions in abdominal and visceral fat [206].

Adiposity refers to the amount of body fat or adipose tissue an individual has. While it is common for highly accessible measures such as body mass index (BMI) to be used in health research, this measure has been shown to be unreliable below threshold values demarking obesity [143, 144], does not account for fat distribution [142], and other methods such as dual-energy x-ray absorptiometry (DXA) have been identified to provide more valid and reliable direct estimates of spatially specific adiposity [145, 146]. In the context of long-term athlete health after sustaining injury during adolescence, adiposity may be an important and revealing objective measure for several reasons, and has been identified to be associated with many negative health outcomes. Previous research has demonstrated that higher levels of adiposity are associated with higher risk of adverse health outcomes such as cardiovascular disease, diabetes, metabolic disease, some forms of cancer, and musculoskeletal disorder/disease [33-35]. Additionally, excess adipose tissue may lead to low-grade chronic inflammation, insulin resistance, and hormonal imbalances [35]. Higher amounts of adiposity may also be concomitant with decreased cardiovascular fitness, muscular strength, and mobility [33, 35]. Lastly, adiposity can also affect psychological health, body image, and self-esteem, which may lead to mental health concerns such as anxiety or depression [34].

As there is a paucity of literature examining long-term athlete health following concussion sustained in childhood or adolescence, reference to longer term health outcomes following musculoskeletal (MSK) injury in adolescence may be relevant. This may be an appropriate comparison as MSK injury too may result in removal from sport participation. While examining body composition in young adults and adolescents (15-26 years of age) with a 3-10 year history of sport-related knee injury (median follow-up time 6.9 years) in youth and adolescent sport, Toomey et al. (2017) found that when compared to sex, age, and sport-matched uninjured controls, individuals with a knee injury history had a higher body mass index (BMI) of 1.79 (range: 0.94 - 2.63), fat mass of 2.3% (range: 0.97 - 3.63), and fat mass index (FMI; kg/m^2) of 1.05 (range: 0.53 - 1.57) [36]. These findings suggest that in the context of MSK injury that BMI, fat mass, and (fat mass index) FMI were associated with long-term knee injury history. In addition to comparing adiposity outcomes in those with 5–15-year adolescent SRC injury history to uninjured controls, it may also be warranted to consider individuals with adolescent MSK injury history as a comparison group. Specifically, examining levels of BMI and FMI identified in this study fail to effectively examine the relationship between injury history and changes to lean mass, the reciprocal of an individual's fat mass in the context of total body mass, which is used to calculate both BMI and FMI [207].

The reality that healing may be affected by age and age may reflect time since injury when isolating for injury sustained in adolescence suggests that age may be an important factor to consider when examining long-term injury history. The severity of tissue damage may however be a difficult factor to consider when examining populations with a variety of injury histories. Despite this, in the context of anterior cruciate ligament (ACL) injury requiring reconstruction, Ardern et al. (2012) identified a relationship between injury severity and time loss from sport [114]. Considering time loss from sport reflects at least a transient change in physical activity behaviors, this highlights the necessity for both injury severity and time loss from injury to be considered in the context of long-term physical activity levels after MSK or SRC injury. Injury severity may also be operationally defined by subsequent time-loss from sport in some sports medicine literature [179] and based on criteria describing sport injury severity, sporting and working time loss as a result of injury are considered among the most relevant [180].

The objective of this study was to examine the body composition of young adults that participated in sport during adolescence, while comparing adiposity via fat mass index (FMI) and lean mass [Lean Mass Index (LMI)] of those with SRC injury history (SRC cohort) and MSK injury history (MSK cohort) to individuals without a significant injury history [Uninjured Controls (UC)]. Another objective of this study was to examine if sex modifies the relationship between injury history and both FMI and LMI as measures of body composition. It was hypothesized that those with SRC and MSK injury history would have higher fat mass and lower lean mass than those without injury history due to a potential decrease in long-term physical activity following these injuries.

4.2 Methods

4.2.1 Participants

Recruitment and data collection was completed from October 2021 to March 2024. Participants were recruited via word of mouth, through the University of Calgary Kinesiology Research website, or based on previously identified sports-related injury if they elected to be contacted for future research while participating in previously completed Sport Injury Prevent Research Centre studies (SIPRC). Potential participants were assessed through a screening interview, requiring them to be between the ages of 16 and 33 years and to have participated in adolescent sport between the ages of 11 and 18. Exclusion criteria included self-report of any significant injury sustained within the last year, medically diagnosed systemic disease, neurological or balance disorder, whiplash, significant psychiatric disorder, or pregnancy. Individuals were assigned to one of three study groups based on their history of concussion and injury: Sport-Related Concussion (SRC) cohort [requiring a sport-related concussion 5-15 years prior to study involvement with a time loss work/school/activities of daily living (ADL) ≥ 7 days and/or medical (physician/physiotherapist) diagnosis], musculoskeletal (MSK) cohort [requiring a sport-related MSK injury 5-15 years prior that resulted in a time loss from work/school/ADL ≥ 7 days], and uninjured control (UC) cohort requiring no significant injury having been sustained. Significant injury, used to define the UC cohort, was defined as any injury resulting in a time loss from work/school/ADL ≥ 7 days, or concussion diagnosis. At 95% confidence, 80% power, and considering a mean of 26 (SD 1.5) minutes per day of accelerometer-measured MVPA for Canadian adults[95], a sample size of 67 per group was required to detect a difference of 10 minutes of MVPA, which is considered a clinically meaningful bout [208].

Study accounts for each participant were created upon successful recruitment on REDCap (Vanderbilt University, Tennessee, United States), a web-based electronic data capture solution [209, 210]. Through individual accounts, participants were provided with all study related information and given the option to provide informed consent to participate. Once participants consented to participate, a testing session was booked within the Human Performance Laboratory, at the University of Calgary, given participant and facility availability. Participation eligibility from screening interviews was cross referenced with demographic, medical, sport participation, and injury history surveys completed by each participant on their personal study account. All data collected from screening interviews, completed surveys, and in-person measures were stored on REDCap and secure private servers within the SIPRC. Ethical approval for the SHRed

Consequences of Concussion study was provided by the University of Calgary's Conjoint Research and Ethics Board (REB21-0548).

4.2.2 Procedures

Dual energy X-ray absorptiometry was used to measure both fat and lean mass as it has been previously used and validated to provide accurate measurements [36, 146]. A General Electric Lunar iDXA X-ray Bone Densitometer scanner (GE Healthcare Lunar, Madison, WI) with manufacturer-licensed software [Encore v18 (2019 GE Healthcare] was used to complete all DXA scans. Daily calibration was completed through a quality assurance scan done prior-to all scanning. Participant height (centimetres) and weight (kilograms) values were acquired immediately prior to each scan and participants were screened for contraindications for scan administration [a) pregnancy and/or b) contrast magnetic resonance imaging within the last 30 days]. After participants were briefed on the nature of the X-ray scanner device, absolute lean and fat masses (grams) were recorded and used to calculate lean mass index (LMI) [absolute lean mass (kg)/height^2 (m)] and FMI [absolute fat mass (kg)/height^2(m)] [211].

4.2.3 Statistical Analysis

Descriptive statistics and statistical analyses were completed using STATAv18 (StataCorp. 2023. *Stata Statistical Software: Release 18*. College Station, TX, StataCorp LLC). Multiple linear regression complete case analysis was performed to examine the relationships between injury SRC injury history, MSK injury history, as well as covariates of interest [i.e., age (years), sex (male/female……), time since injury, time loss from injury)] and FMI and LMI in independent models. Interactions between sex and covariates of interest were assessed and retained in each regression model at $p<0.1$. Due to non-parametric distribution, log transformation was completed prior to multiple linear regression modelling for FMI. Average marginal effects of each covariate on LMI and log back-transformed average marginal effects of each covariate on FMI were provided for meaningful interpretation of results. An a-priori alpha of 0.05 was used.

4.3 Results

4.3.1 Descriptive Statistics & Recruitment

Contact was attempted for 4,793 individuals via previous research studies, word of mouth, or through University of Calgary Research website participation. Failure to reach participants occurred for 3,525 of individuals from previous cohort studies. Additionally, 475 parent/family members were contacted in the participants stead where 332 took study information and/or provided updated contact information. The most common reason for individuals declining to participate was moving to another city (n=60; 60.5%) since previous study involvement. In total, 329 individuals (6.9% of all attempted contacts) met inclusion criteria and consented to participate. Of 329, 143 (46.5%) were reached through previous study involvement, 168 (51.1%) via word of mouth, and 8 (2.4%) through the research website. Of 329 individuals that were successfully recruited and provided informed consent to participate, 268 followed through with attending in-person testing sessions.

Due to non-parametric distribution of the covariate time since injury, median time since initial injury for injury groups was used to impute values for the UC for complete case analysis. Similarly, mean time loss from injury for injury groups was used to impute values for the UC cohort. Seven individuals (2 SRC, 2 MSK, 3 UC) did not complete DXA scans, 4 individuals failed to report time since injury (2 SRC, 2 MSK), and 1 SRC failed to report time loss from injury, resulting in a total of 10 individuals of 268 not being included in complete-case analysis. Table 1 displays the distribution of participants by injury cohort and sex. A total of 100 SRC (54 male, 46 female), 84 MSK (45 male, 39 female), and 84 UC (38 male, 46 female) were included in analysis.

Table 2 displays means and standard deviations for both outcomes (FMI and LMI) and covariates of interest. The average mean age for all individuals was 23.48 years (SD 3.81). Injury cohort-sex heights and weights [mean (SD)] are displayed as they are required for FMI, LMI, and BMI calculation, which are also displayed (Table 2). Mean (SD) time since initial injury for all participants was 8.56 (3.34) years. Median (IQR) days of time loss from injury was higher for the MSK cohort with males at 36 (21-60) and females at 40 (21-63) compared to SRC males at 14 (7-28) and females 14 (7-30). Mean (SD) male BMI, FMI, and LMI were respectively 24.69 (3.62), 5.22 (2.36), and 18.46 (2.14). Mean (SD) female BMI, FMI, and LMI were respectively 23.41 (4.29), 7.21 (3.20), and 15.19). Sex differences for FMI and LMI are summarized in Tables 3-6.

4.3.2 Fat Mass Index

Table 3 summarizes results from the log transformed complete case multiple linear regression model examining FMI by cohort and adjusting for sex, age, time since injury, and time loss from injury. Interaction between sex and other covariates on FMI was not identified ($p>0.1$) and terms were not retained in the model. SRC (logβ=0.063, 95%CI: -0.056, 0.172; $p=0.297$) and MSK (logβ=-0.057; 95%CI: 0.410, -0.193; $p=0.079$) injury history did not have an association with FMI relative to UC. Sex was found to have an association with FMI with males having a lower FMI (logβ=-0.341; 95%CI: -0.437, -0.244; $p<0.001$) than females. Age per 1 year increase (logβ=0.003; 95%CI: -0.014, 0.020; $p=0.707$), time since injury per 1 year increase (logβ=0.008; 95%CI: -0.014, 0.031; $p=0.464$), and time loss from injury by 1 day increase for

SRC (logβ=0.001; 95%CI: -0.001, 0.001; p=0.244) or MSK (logβ=0.001; 95%CI: -0.001, 0.002; p=0.113) cohorts all had positive relationships with FMI.

Table 4 displays back transformed average marginal effects of injury cohort and covariates on FMI. Those with SRC injury history did not differ regarding FMI (0.499; 95%CI: -0.230, 1.228) relative to UC (mean=5.947, 95%CI: 5.489, 6.405) nor did those with MSK injury history (-0.131; 95%CI: -0.858, 0.596). The average marginal effect of male sex relative to female (mean=7.215, 95%CI: 6.655, 7.774) on FMI was -2.100 (95%CI: -2.708, -1.491). Average marginal effects on FMI were 0.020 (95%CI: -0.084, 0.124) for every one-year increase in age and 0.052 (95%CI: -0.087, 0.191) for every one-year increase in time since injury. Average marginal effect on FMI for one-day increases in time loss from injury for the SRC cohort was 0.003 (95%CI: -0.002, 0.007) and 0.005 (95%: -0.001, 0.011) for the MSK injury cohort.

4.3.3 Lean Mass Index

Table 5 displays results from the complete case multiple linear regression analysis examining LMI by cohort while adjusting for age, sex, time since injury, and time loss from injury. Interaction between sex and any other covariate on LMI was not identified (p>0.1) and terms were not retained in the model. Relative to UC, SRC injury had a positive (β=0.689; 95%CI: 0.138, 1.240; p=0.014) association with LMI. No association was identified between MSK injury history and LMI (β=0.290; 95%CI: -0.341, 0.922; p=0.366) relative to UC. Male relative to female sex had a positive association (β=3.18; 95%CI: 2.731, 3.629; p<0.001) with LMI. Age also had a positive association (β=0.090; 95%CI: 0.012, 0.168; p=0.024) with LMI. Time since injury had an insignificant negative (β=-0.006; 95%CI: -0.110, 0.098; p=0.912) association with FMI. No association between time loss by injury cohort and LMI for both SRC (β=0.002; 95%CI: -0.001, 0.005; p=0.236) and MSK (β=0.003; 95%CI: -0.002, 0.008; p=0.182) injury cohorts relative to UC was identified.

Table 6 displays average marginal effects of injury cohort and covariates on LMI. Individuals with SRC injury history had a 0.780 higher LMI (95%CI: 0.240, 1.320) relative to UC with a mean LMI of 16.144. The average marginal effect of MSK injury history on LMI was 0.405 (95%CI: -0.167, 0.977) relative to UC. Males relative to females had a 3.159 increase in LMI (95%CI: 2.713, 3.605) and 1-year increases in age also increased LMI by 0.092 (95%CI: 0.014, 0.169). The average marginal effect of time since injury per 1-year increase was a subsequent increase in LMI by 0.004 (95%CI: -0.099, 0.108). Average marginal effects of one-day increase in time loss from injury for SRC and MSK injury cohorts on LMI were respectively 0.002 (95%CI: -0.001, 0.005) and 0.003 (95%CI: -0.002, 0.008).

4.4 Discussion

This study investigated a sample of young adults (18-33 years of age) and examined body composition outcomes via fat-mass and lean-mass indices after experiencing either SRC or MSK injuries 5-15 years prior during adolescence.

The main findings were that contrary to what was hypothesized, body composition as indexed through FMI or LMI outcomes via DXA imaging were no different between those with injury history relative to uninjured controls (Tables 3-6). Only one significant association was found and ran contrary to what was hypothesized, with the SRC injury cohort having higher LMI than the uninjured (Tables 5 & 6). While examining the role sex may have on any of the covariates of interest (injury history, age, time since injury, and time loss from injury) and FMI/LMI outcomes, no effect modification was identified. Sex differences were identified with respect to FMI and LMI, where males relative to females had higher fat mass and lower lean mass indices.

With no associations between injury history and FMI outcomes identified and mean FMI values for all three cohorts being within normal ranges of 3-6 for males (SRC 5.4±2.4, MSK 4.9±2.1, UC 5.4±2.4) or 5-9 for females (SRC 8.0±4.0, MSK 7.3±3.4, 6.4±1.6)), based on WHO BMI matched classifications for FMI [166], it is reasonable to suggest that those with injury history in the present study were able to attain and/or maintain healthy adiposity levels. This is encouraging as it suggests that SRC injury history from adolescence may not pose long-term threats to unhealthy changes in adiposity. However, previous literature has identified that racial/ethnic differences, in addition to cofactors such as age and sex, that exist with respect to diseases like diabetes that are concomitant with excess adiposity as well as measures of visceral adipose tissue need also be interpreted [151-155].

Despite adolescent concussion history potentially leading to shifts in attitudes and perceptions towards physical activity through sport participation [102, 212], plausible increases in sedentary behavior [102], and being linked to persistent symptoms related to concussion [213], no meaningful associations between long-term injury history and changes to body composition were identified. In the context of MSK injury history, the present study also failed to identify differences in measures of adiposity in this cohort relative to the uninjured where previous similarly designed studies have [36]. However, the aforementioned study examined specifically knee injuries severe enough to require intervention and may highlight the heterogeneity of injuries and injury severities in the present study. This may suggest that other factors need be considered when examining long-term injury histories and/or that our definition of *'significant'*, requiring a time loss from sport/school/work/activities of daily living equal to or greater than a week, may not be impactful enough to effect physical activity behaviors 5-15 years after initial injury.

Previous literature identifying positive associations between injury severity and time loss from sport [114, 179] suggested that time loss may be an effective way to interpret injury severity and adjust for it in the context of long-term injury history in adults whom sustained SRC or MSK injury 5-15 years prior during adolescent sport. Additionally, epidemiological models examining the recurrent nature of sport-related injury have highlighted time loss as one of the more important factors to consider in the context of injury severity [180]. Despite this, no associations between time loss from injury and FMI or LMI outcomes were identified. This may further suggest that other factors such as persistent symptoms in the context of SRC need to be considered when examining long-term health outcomes. Previously identified psychosocial effects of SRC such as fear of recurrent concussion and injury [104], removal from sport [30], and level of support obtained during recovery [105] were considered as plausible explanations for both short term and plausibly long term changes to movement behaviours and thus consequent alterations to body composition in adulthood. However, the present study failed to identify and consequently interpret how or why changes to movement behaviors may occur. Additionally, while sex was considered, important cofactors such as gender were not interpreted as only 3 of the 268 individuals included in these analyses identified as non-binary.

4.5 Limitations and Future Directions

A limitation of the present study may be as to why no associations were identified between injury history and FMI in that significant heterogeneity of MSK and SRC injury histories were present. Here, future research may benefit from stratifying MSK injury history into upper extremity and lower extremity injuries which may lead to findings more congruent with previous research that focused on lower extremity injuries [36]. Heterogeneity in SRC symptom presentation, clinical presentation, and recovery trajectories in acute settings has already been identified in previous research [214], and thus examining long-term concussion-related symptomology in the context of long-term sequalae of concussion is warranted. A potential way to incorporate concussion-related symptomology in individuals with a long-term SRC injury history may be utilizing the validated symptom evaluation of the sideline SRC screening device, the Sport Concussion Assessment Tool [215, 216].

Given the identified potential psychosocial impacts of concussion on sport participation, it may be warranted to identify and examine both when and why individuals may have stopped participating in sport. Additionally, while sex was considered, important cofactors such as gender [217] were not able to be examined as only 3 of the 268 individuals included in these analyses identified as non-binary. The necessity to examine gender may be further implored as individuals that do not conform to heteronormative gender identities are often overlooked or poorly captured under umbrella terms in much scientific research [218].

Another limitation of the study may be the sampling frames of recruitment sources, with recruitment being largely dichotomized between word-of-mouth and previous cohort study involvement. Word-of-mouth recruitment involved individuals working at the Sport Injury Prevention Research Centre within the University of Calgary's Faculty of Kinesiology. It is plausible that individuals recruited here may be more well educated within the Kinesiology field and more inclined to engage in physical activity behaviours. A sensitivity analysis (Appendix A) was completed for FMI and LMI models by adjusting for recruitment source. Previous associations found (Tables 3 & 5) did not change marginally when adjusting for recruitment source, and interaction between recruitment source and cohort or sex was not identified. However, this does not remove the possibility for selection bias to have influenced aggregate LMI or FMI values. Lastly, multiple injury history was not assessed in the present study and some individuals placed in the SRC cohort also had MSK injury history (n=30, 30%). However, as concussion injury history was unique to the SRC cohort, this was identified as a non-issue.

4.6 Conclusion

In the context of long-term (5-15 year) concussion injury history for adults (ages 18-33), no differences were identified between those with SRC or MSK injury history when compared to uninjured controls. In fact, LMI was found to be higher in individuals with SRC injury history. These findings are encouraging as they suggest that those who sustain SRC or MSK injury during adolescence remain healthy with respect to measures of fat mass or lean mass indices. Subsequently, healthcare professionals should focus on providing effective care to adolescents that sustain SRC and focus on facilitating an efficient and effective return to play or return to sport. Future research should focus on factors such as persistent long-term concussion-related symptoms and find ways to best address heterogeneity of the injury when examining long-term health outcomes as this may help better examine the long-term sequalae of concussion injury.

4.7 Tables

Table 1. Sex-Cohort Distribution for Individuals Included in Analysis

Cohort	Male	Female	Total
SRC	54	46	100
MSK	45	39	84
UC	38	46	84
Total	137	131	268

**Sport-Related Concussion (SRC), Musculoskeletal (MSK), Uninjured Control (UC).*

Table 2. Descriptive Statistics for Outcomes and Covariates by Injury Cohort and Sex

	SRC		MSK		UC	
	Male	Female	Male	Female	Male	Female
Age, years	23.7(3.9)	23.7(3.5)	24.4(4.0)	23.6(3.8)	23.5(4.3)	22.0(3.2)
Time since, years	8.9(3.6)	8.3(3.3)	8.4(3.4)	8.5(3.1)	-	-
Time loss, days	14 (7-28)	14 (7-30)	36 (21-60)	40 (21-63)	-	-
Height, centimetres	182.0(6.5)	167.0(6.7)	180.9(6.4)	171.0(5.5)	176.4(6.7)	167.7(7.2)
Weight, kilograms	83.3(14.7)	68.6(15.6)	80.0(12.6)	69.4(12.3)	75.8(12.6)	62.5(9.6)
BMI	25.1(4.0)	24.6(5.4)	24.3(3.1)	23.9(4.1)	24.6(5.4)	21.8(2.4)
FMI	5.4(2.5)	8.0(4.0)	4.9(2.1)	7.3(3.4)	5.4(2.4)	6.4(1.6)
LMI	18.8(1.9)	15.6(1.7)	18.4(1.9)	15.5(1.2)	18.2(2.2)	14.5(1.4)

**Body Mass Index (BMI), fat mass index (FMI), lean mass index (LMI), all variables [mean (standard deviation)] except time loss [median (interquartile range)].*

Table 3. Log Transformed Linear Regression Model for Fat Mass Index

	Beta	P-value	95%CI	
Cohort				
SRC Injury (relative to UC)	0.063	0.297	-0.056	0.182
MSK Injury (relative to UC)	-0.057	0.410	-0.193	0.079
Sex (Male relative to Female)	-0.341	<0.001	-0.437	-0.244
Age (every one-year increase)	0.003	0.707	-0.014	0.02
Time Since (every one-year increase)	0.008	0.464	-0.014	0.031
Time Loss by Cohort				
SRC (relative to UC)	0.001	0.244	-0.001	0.001
MSK (relative to UC)	0.001	0.113	-0.001	0.002

**Sport-Related Concussion (SRC), Musculoskeletal (MSK), Uninjured Control (UC).*

Table 4. Back Transformed Average Marginal Effect on FMI by Covariate

	Contrast	95%CI	
Cohort			
SRC Injury (relative to UC)	0.499	-0.23	1.228
MSK Injury (relative to UC)	-0.131	-0.858	0.596
Sex (Male relative to Female)	-2.100	-2.708	-1.491
Age (every one-year increase)	0.020	-0.084	0.124
Time Since (every one-year increase)	0.052	-0.087	0.191
Time Loss by Cohort			
SRC (relative to UC)	0.003	-0.002	0.007
MSK (relative to UC)	0.005	-0.001	0.011

**Sport-Related Concussion (SRC), Musculoskeletal (MSK), Uninjured Control (UC).*

Table 5. Linear Regression Model for Lean Mass Index by Covariate

	Beta	P-value	95%CI	
Cohort				
SRC Injury (relative to UC)	0.689	0.014	0.138	1.240
MSK Injury (relative to UC)	0.290	0.366	-0.341	0.922
Sex (Male relative to Female)	3.180	<0.001	2.731	3.629
Age (every one-year increase)	0.090	0.024	0.012	0.168
Time Since (every one-year increase)	-0.006	0.912	-0.110	0.098
Time Loss by Cohort				
SRC (relative to UC)	0.002	0.236	-0.001	0.005
MSK (relative to UC)	0.003	0.182	-0.002	0.008

**Sport-Related Concussion (SRC), Musculoskeletal (MSK), Uninjured Control (UC).*

Table 6. Average Marginal Effect for Lean Mass by Covariate

	Contrast	95%CI	
Cohort			
SRC Injury (relative to UC)	0.780	0.240	1.320
MSK Injury (relative to UC)	0.405	-0.167	0.977
Sex (Male relative to Female)	3.159	2.713	3.605
Age (every one-year increase)	0.092	0.014	0.169
Time Since (every one-year increase)	-0.004	-0.108	0.099
Time Loss by Cohort			
SRC (relative to UC)	0.002	-0.001	0.005
MSK (relative to UC)	0.003	-0.002	0.008

Sport-Related Concussion (SRC), Musculoskeletal (MSK), Uninjured Control (UC).

Chapter 5. Consequences of sport-related adolescent concussion: examining 5–15-year physical activity behaviours

5.1 Background

Fifty percent of an annual estimate of 3 million people sustaining a concussion injury from sports or recreation activities in North America are children or adolescents [53]. Risk of sport-related concussion increases when participating in contact or collision sport(s) and an estimated 1 in 9 (11.1%) Canadian adolescents experience a concussion during sport participation [9, 54]. Concussions can be debilitating injuries that may affect physical, mental, financial, and academic well-being of an individual [55]. The 6th International Conference on Concussion in Sport – Amsterdam October 2022 – defined a sport-related concussion (SRC) as *"a transient disruption in neurological function induced by biomechanical forces transmitted to the brain by either a direct or indirect blow to the head or body"* [15]. A call for a well-developed multifaceted research and funding to develop a greater understanding of long-term (concussion history ≥5 years) athlete health after concussion was made within the most recent series of systematic reviews informing the consensus statement on concussion in sport [15, 45].

Parental removal from sport as a result of concussion [30], level of support obtained during recovery [105], and fear of recurrent concussion injury in those with previous concussion history [104] may be factors influencing return to play decisions and return to sport timelines. Additionally, a significant proportion of athletes fail to return to sport participation at the same level of play after SRC [219] These psychosocial factors may suggest it is plausible for concussion injuries sustained during adolescent sport participation to have profound effects on long-term sport participation and/or physical activity (PA) behaviors.

Physical activity and sedentarism are both aspects of PA behaviours that occur throughout a 24-hour window. PA can be defined as a bodily movement produced by skeletal muscles that requires energy expenditure above and beyond basic metabolic demands [63]. PA guidelines for Canadian adults (ages 18-64) include, but are not limited to: accumulation of 150-minutes of moderate-to-vigorous PA (MVPA) per week, muscle/strength training activities at least twice per week, and several hours of light physical activities [78]. Sedentary behaviour (SB) may be defined as any waking behaviour that requires an energy expenditure ≤1.5 metabolic equivalents (MET), often occurring in a sitting, reclined or supine posture [65]. Engaging in PA can reduce the risk of developing chronic diseases such as heart disease, stroke, and diabetes [66], and can also improve mental health and cognitive function [67]. An assortment of mechanisms such as improved synaptic plasticity, perfusion, and neurogenesis, have been able to show how PA can delay age-related cognitive declines in adults [5-7]. The health benefits of PA extend well beyond just physical health measures. Improvements in cognitive function, emotional well-being, social health, and perceptions of psychological well-being have all been identified to be associated with PA behaviours [1, 2]. The numerous benefits to PA behaviours have been shown to typically outweigh the risks, despite well-established factors associated with sport participation [14]. The negative consequences of SB may include reduced cardiovascular health, where SB may also increase the risk of obesity and hormone-related cancer(s) through decreased lipoprotein lipase activity, altered hormone levels, lessened lipid and carbohydrate metabolism, and decreased insulin sensitivity [68].

In keeping with the most recent consensus statement on concussion calling for research into the long-term (≥5 years) following the injury, there is a paucity of literature examining longer-term (greater than 2 years post-injury) effects of concussion (inclusive of SRC and mTBI) on physical activity (PA), which is consistent with a review examining all later-in-life sequalae after concussion [45]. There is also a gap in the literature examining the consequences of concussion beyond the acute post-injury setting in the context of PA levels. In particular there is a lack of examination of objective outcome measures seeking to examine and quantify PA levels in individuals with a history of concussion. A systematic review and meta-analysis have demonstrated appropriate amounts of post-injury PA have a positive association with symptom resolution after concussion, however differences in PA behaviors in previously concussed populations have not been established over a long-term (≥5 years) post-injury setting [20]. Previous research examining objectively-measured levels of PA 3-12 years post-sport-related knee injury in adults aged 18-35 has demonstrated those with a history of knee injury had lower levels of MVPA when compared to healthy controls with similar age-, sex-, and sport-characteristics [29]. This finding in the longer-term following knee injury indicates it may be useful to compare both long-term SRC and musculoskeletal (MSK) injury to better understand the magnitude of effect of adolescent injury history on PA levels later in life.

Isolating the long-term effects of adolescent sport-related injury on PA behaviors may be a challenging task as several injury-related corelates could influence these behaviors, as they may in short-term or acute-post injury settings. For example, previously identified relationships between time loss from sport and injury severity exists in the context of ACL injury [114]. This highlights the necessity for both time loss as a result of injury and injury severity to be considered when examining the effects long-term SRC or musculoskeletal injury may have on PA behaviors such as sedentarism or daily amounts of light activity and/or MVPA. Fortunately for long-term sports injury research, previous sports medicine research has quantified injury severity by associating the injury with the subsequent time loss [179]. Additionally, seminal research examining the recurrent nature of sport-related injury describes time loss from sport or work as fundamental criteria that may define severity of an injury [180].

The purpose of this study was to examine PA behaviours [daily minutes of MVPA, light physical activity (LPA), moderate physical activity (MPA), vigorous physical activity (VPA)], and sedentary time] in young adults with a long-term (≥5 year) history of SRC or MSK injury sustained in adolescence and compare to uninjured controls (adjusting for age, sex, time since injury, and time loss from injury). Another objective of this study was to examine the extent that biological sex modifies the relationship between injury history and PA behaviors. An exploratory objective of this study was to examine if daily MVPA and sedentary time is accrued through different amounts of bouts. It was hypothesized those with SRC and MSK injury history would have lower levels of daily LPA and MVPA, and higher levels of daily sedentary time than those without injury history.

5.2 Methods

5.2.1 Participants

Recruitment and data collection October 2021 to April 2024. Participants were recruited through previous participation in Sport Injury Prevention Research Centre (SIPRC) studies where sport-related injury history information was collected, University of Calgary Research website outreach, or word-of-mouth. All individuals successfully contacted were screened briefly through phone call interviews assessing injury and medical histories. Individuals that passed screening interviews were assigned to either SRC, MSK, or and uninjured control (UC) cohort. Individuals with one or more qualifying SRC injury sustained 5-15 years ago during adolescent sport (ages 11-18) that resulted in a time loss from sport, school, work, or activities of daily living (ADL) ≥1 week were assigned to the SRC cohort. Individuals with one or more qualifying MSK injury sustained 5-15 years ago during adolescent sport that resulted in a time loss from sport, school, work, or ADL ≥1 week were assigned to the MSK cohort. Individuals with no significant injury history [significant defined as any injury resulting in a time loss from sport/school/work/ADL ≥1 week or physician/physiotherapist diagnosed concussion] were assigned to the UC cohort. All participants at time of screening and data collection were required to be between 18 and 33 years of age, not be pregnant, and have no history of significant psychiatric/balance disorder, medically diagnosed systemic/neurological disease, or medically diagnosed whiplash/neck pain of traumatic or non-traumatic origin.

At the end of a successful screening interview participants were provided a link to create a SHRed Consequences of Concussion study account through the web-based electronic data capture system REDCap (Vanderbilt University, Tennessee, United States) [209, 210]. Here, participants were provided all study related information and were required to provide informed consent prior to completing demographic, medical, and injury history surveys. Once completed, to confirm study eligibility surveys were cross-referenced by a research coordinator with the information provided in screening interviews, then each participant was assigned a unique universal identification number (UUID) linking all surveys and data collected from testing procedures to the participant. Once assigned a UUID participants were booked in to attend in-person testing in the Human Performance Laboratory, University of Calgary, based on their as well as facility availability. The SHRed Consequences of Concussion study received ethics approval from the University of Calgary's Conjoint Research and Ethics Board (REB21-0548).

5.2.2 Procedures

During in-person testing procedures, participants were provided with initialized GT3X+ ActiGraph (ActiGraph LLC) triaxial linear accelerometer units as ActiGraph activity monitors can differentiate between sedentary and PA behaviors and have been previously used in pediatric and adult populations [115, 118]. ActiGraph use has also been validated in previous studies for adult populations [116, 119] and adults in free-living conditions [120]. Participant sex, height, weight, and dominant hand information required for device initialization were self-reported prior to device administration. Participants were requested to wear the device above the anterior-superior iliac spine on their dominant-arm side during waking hours for seven consecutive days after successful recruitment to the study. ActiLife v6.13.4 (2009-2015 ActiGraph LLC) was used for wear-time validation once the devices were either picked up by a research coordinator or returned to the SIPRC office by the participant. The Choi (2008) wear-time validation algorithm provided by ActiLife software was used for wear-time validation after device data was downloaded to private and secure servers [195]. Hourly wear-time data was visually inspected and cross-referenced to daily wear-time logs the participants were requested to complete after each day wearing the device, where non-wear time(s), wake-up time, and bedtimes were self-reported. A day of wear-time was included in analysis if it consisted of equal to or greater than 10-hours of wear-time for individuals with 4 or more days of wear time [220]. The Troiano (2008) cut-point algorithm designed to capture activity intensities in adults under free-living conditions [124] was used to quantify daily minutes of MVPA, LA, MA, and VA. In addition, daily bouts (1 bout $\geq$ 10 minutes) of MVPA and sedentary activity were evaluated.

5.2.3 Statistical Analysis

Descriptive statistics and formal analyses were completed using STATAv18 (StataCorp. 2023. *Stata Statistical Software: Release 18*. College Station, TX, StataCorp LLC). Outcome distributions were assessed visually as well as through Shapiro Wilks normality tests to appropriately fit models. Multiple linear regression complete-case analyses [daily minutes of MVPA, LA, MA], generalized linear modelling with gamma distribution and logarithmic link [daily minutes of VA], and Poisson regression complete-case analyses [MVPA bouts/sedentary bouts] were completed. The exploratory outcome of MVPA bouts and sedentary bouts included Poisson regression complete-case analyses controlling for daily MVPA or sedentary time by treating them as exposure variables, respectively, and estimating incidence rate ratios (IRR) to provide bout rates [# bouts/day]. One bout was calculated as ≥ 10 continuous minutes of either MVPA or sedentary time. This allowed for determining if total daily minutes of both MVPA and sedentary time were accrued through a different number of daily bouts. All regression models were completed while adjusting for covariates of interest [sex (male, female), age (years), time-since initial injury (years), and time loss from injury (days)]. Effect modification of sex on injury cohort and other covariates of interest was assessed, and significant ($p<0.10$) interaction terms were retained in each model. An *a-priori* alpha level was set at 0.05.

5.3 Results

5.3.1 Descriptive Statistics & Recruitment

An attempt to contact potential participants to determine interest and eligibility was made for 4,793 individuals. Inability to reach an individual resulted occurred for 3,525 (73.5%), primarily due to out of service numbers from previous cohort studies. For individuals that were reached, the most common reason for declining to participate was moving to another city (n=60) since previous study involvement. In total, 329 individuals (6.9% of all attempted contacts) met inclusion criteria and consented to participate. Of these 329,143 (46.5%) were reached through previous study contact information, 168 (51.1%) word of mouth, and 8 (2.4%) reached out through the research website. In-person testing procedures were attended by 268 individuals [61 (18.5%) lost to follow up] where ActiGraphs were initialized. Devices were only given to 248 (92.3%) individuals as 20 (7.7%) declined to wear the device. In all, 203 individuals of 268 (75.7%) wore ActiGraph devices sufficiently for data to be included in analyses based on a-priori wear-time inclusion criteria.

There were total of 100 SRC (54 male, 46 female), 84 MSK (45 male, 39 female), and 84 UC (38 male, 46 female). Sufficient wear-time resulted in ActiGraph data from 76 SRC (40 male, 36 female), 64 MSK (32 male, 32 female), and 63 UC (24 male, 39 female) being included in the analyses. Four individuals failed to report time since injury appropriately (2 SRC, 2 MSK), subsequently resulting in 4 individuals being excluded from analyses due to missingness. Sex-cohort descriptive statistics for outcomes and covariates of interest are provided (Table 1). Median time since initial injury and time loss from for both injury groups was used to impute values for the UC cohort for complete case analysis as the covariates were non-parametrically distributed. MVPA and sedentary bouts are provided as incidence rate ratios (IRR) with 95% confidence intervals (CI), with sex-cohort raw MVPA and sedentary bout IRRs being equal to the mean number of daily bouts (Table 2).

5.3.2 Moderate-to-Vigorous Physical Activity

Results from the multiple linear regression complete case analysis examining daily MVPA minutes adjusting for injury cohort, sex, age, time since initial injury, and time loss from injury are displayed (Table 4). No effect modification by sex on any covariates of interest were identified and retained in the model. There were no differences observed in daily MVPA time in minutes for SRC [53.69 (95%CI: 48.00, 59.38)] and MSK cohorts [53.90 (95%CI: 47.54, 60.28)] relative to UC [50.04 (95%CI: 44.40, 55.67)] [$\text{difference}_{SRC\text{-}UC}$ = 3.16 (95%CI: -5.34, 11.65; p=0.434) & $\text{difference}_{MSK\text{-}UC}$ = 4.04 (95%CI: -4.93, 13.01; p=0.376)]. No difference [male relative to female, 4.11 (95%CI: -2.95, 11.17; p=0.252)] was observed in daily MVPA minutes between males [54.83 (95%CI: 49.74, 59.92)] and females [50.65 (95%CI: 46.15, 55.15)]. There were also no observed associations between MVPA and age [every one-year increase in age, 0.27 (95%CI: -1.40, 1.93; p=0.751)], time since injury [every 1-year increase in time since injury, 0.27 (95%CI: -1.39, 1.94; p=0.745)], or time loss from injury [-0.004 (95%CI: -0.04, 0.03; p=0.826), every 1-day increase in time loss from injury].

5.3.3 Light Physical Activity

Results from the multiple linear regression complete case analysis examining daily minutes spent in LPA adjusting for covariates of interest are provided (Table 3). No effect modification by sex on any covariates were identified and retained in the model. There were no differences between groups for minutes spent engaging in daily LPA for SRC [206.80 (95%CI: 193.36, 220.24) and MSK [193.81 (95%CI: 178.42, 209.19)] cohorts relative to UC [193.61 (95%CI: 178.43, 208.80)] [$\text{difference}_{SRC\text{-}UC}$ = 14.93 (95%CI: -5.19, 35.05; p=0.145) & $\text{difference}_{MSK\text{-}UC}$ = 0.71 (95%CI: -20.55, 21.97; p=0.947)]. No difference in minutes spent engaging in daily LPA [-4.40 (95%CI: -21.13, 12.32; p=0.604)] was observed for males [197.24 (95%CI: 184.75, 209.72)] relative to females [199.85 (95%CI: 188.51, 211.18)]. No associations between covariates of interest and LPA were observed (Table 3).

5.3.4 Moderate & Vigorous Physical Activity

Results from the multiple linear regression examining daily minutes spent in MPA and generalized linear modelling examining daily minutes spent in VPA are displayed (Table 3). No effect modification by sex on any covariates of interest for both MPA and VPA were identified and retained. No associations were found between cohort, sex, age, time since injury, or time loss from injury and MPA or VPA (Table 3).

5.3.5 Sedentary Time

Results from the multiple linear regression complete case analysis examining daily sedentary minutes adjusting for injury cohort, sex, age, time since initial injury, and time loss from injury are displayed (Table 4). No effect modification by sex on any covariates of interest were identified. No differences were identified for daily sedentary time in minutes for SRC [557.94 (95%CI: 538.71)] and MSK [553.35 (95%CI: 532.18, 574.52)] cohorts relative to UC [553.89 (95%CI: 533.50, 574.28)] [$\text{difference}_{SRC\text{-}UC}$ = -1.00 (95%CI: -30.21, 28.21; p=0.946) & $\text{difference}_{MSK\text{-}UC}$ = -7.92 (95%CI: -41.14, 25.30; p=0.639). There was no difference between daily sedentary minutes for males [562.22 (95%CI: 543.81, 580.63)] and females [548.96 (95%CI: 534.57, 563.36)] [$\text{difference}_{M\text{-}F}$ = -0.31 (95%CI: -4.28, 3.66; p=0.877). No associations were identified between covariates of interest and daily minutes of sedentary time (Table 4).

5.3.6 Bouts

Results from Poisson regression complete-case analyses by covariate examining MVPA and sedentary bouts with daily minutes of MVPA and sedentary time exposure, respectively, are displayed (Table 5). Results from Poisson models without daily MVPA or sedentary time exposure are provided for reference (Table 5). Controlling for daily minutes of MVPA, rates of daily sedentary bouts for SRC were 0.85 (95%CI: 0.59, 1.24; p=0.410) and 1.08 (95%CI: 0.75, 1.57; p=0.669) for MSK relative to UC. Controlling for daily minutes of MVPA, daily rates of MVPA bouts were 1.02 (95%CI: 0.75, 1.57; p=0.669) for males relative to females, 0.96 (95%CI: 0.91, 1.01; p=0.115) per one-year year increase in age, and 1.05 (95%CI: 0.98, 1.13; p=0.164) per one-year increase in time since injury. Controlling for daily minutes of sedentary time, daily rates of sedentary bouts for SRC were 0.92 (95%CI: 0.84, 1.01; p=0.0.075) and 0.99 (95%CI: 0.90, 1.09; p=0.892) for MSK relative to UC. Controlling for daily minutes of sedentary time, daily rates of sedentary bouts were 1.07 (95%CI: 1.00, 1.09; p=0.064) for males relative to females. No associations between covariates of interest and bouts as whole were identified but all IRR estimates are provided (Table 5).

5.4 Discussion

The primary findings from this study were that while adjusting for sex, age, time since injury, and time loss from injury, no differences in daily amounts of MVPA, LA, MA, or VPA were identified for SRC or MSK injury cohorts relative to the uninjured (Table 3). This is highly encouraging as it suggests that those with significant SRC or MSK injury sustained ≥5 years ago continue to engage in lifestyles that are at least as physically active as the UC. Biological sex was not found to modify the relationships between injury cohort or any of the covariates of interest and any PA behavior outcomes, suggesting that in the context of long-term SRC or MSK injury in those that were active as adolescents (ages 11-18) physical activity levels do not differ for males and females.

The findings from this study are encouraging, especially considering that overall individuals in our study averaged daily amounts of MVPA (48.21 minutes) and LPA (187.48 minutes) exceeding currently recommended Canadian guidelines of ≥150 minutes of MVPA and several hours of LPA per week [129]. Additionally, individuals in this study averaged greater amounts of all-intensity physical activity than previous higher-powered accelerometer-derived study of the Canadian general population [95]. Regarding how daily amounts of MVPA were accrued, no differences were identified for rates of clinically significant [221, 222] MVPA bouts ≥10 minutes. However, those with SRC and MSK injury history achieved comparable amounts of daily MVPA through 15% fewer and 8% more bouts, respectively. This may be interpreted as aggregate MVPA time being accrued through longer unbroken sessions for SRC and shorter more frequent sessions for MSK cohorts. How this impacts the recommendation for breaking-up extended sedentary time [129] requires examining sedentary bouts as they may be broken by LPA or MVPA. As average daily sedentary minutes were similar across groups and sexes [555.93 (95%CI: 543.75, 466.72)], the rate of daily sedentary bouts ≥10 minutes determines how this time is broken up by any PA. While cohort and covariates had no identified association with number of bouts, IRR estimates for history of SRC and MSK injury resulted in accruing sedentary time through 8% (p=0.075) and 1% (p=0.892) fewer sedentary bouts, respectively, relative to UC. While 1% may be nominal for MSK, 8% fewer bouts of sedentary time for the SRC indicates this cohort may have engaged in longer periods of sedentarism.

5.5 Limitations and Future Directions

This study screened for and included only individuals with identified previously physically active lifestyles as adolescents (ages 11-18) and thus generalizability to the Canadian general population may be limited. Successful recruitment for this study through word-of-mouth and previous cohort study involvement sampling frames may pose limitations through sampling bias. However, sensitivity analyses of MVPA, LA, MA, and VPA outcomes (Appendix B) through additionally adjusting for recruitment source yielded non-significant findings. Objectively measured free-living PA through Actigraphy for this study required individuals to a) wear the device appropriately, and b) self-report their device wear-times, potentially affecting wear-time validation. Wear-time validation involved algorithm defined conflicts regarding wear- and non-times [195] where suspect non-wear times were cross-referenced with participant self-reports. If cross-referencing did not dictate whether a period reflected wear or non-wear time, it was addressed conservatively which could potentially yield a nominal level of measurement bias through underestimations of sedentary outcomes. We would expect this to be nondifferential between groups or sexes as wear-time validation procedures were consistent across all participants, however, conservative wear-time validation could bias subtle daily sedentary time outcomes towards the null.. To address possibility for selection bias regarding the 20 individuals that declined to wear and 45 who did not meet wear-time inclusion criteria by failing to wear the device appropriately, cohort proportions were provided (Appendix C) and suggest they are nondifferential across cohorts. A limitation to this study was posed through recall bias as participants were required to provide an accurate time for their initial injury as well as time loss from this injury. While this likely would not have effected time since injury marginally or the median value imputed for UC, significant injuries requiring ≥ 7 days time loss indicates a possibility for misclassification.

This study failed to identify the hypothesized differences that have been demonstrated in previous studies examining lower extremities MSK injuries [29, 207]. We suspect this is due to large heterogeneity in how SRC symptoms and persistent symptoms present as well as heterogeneity in MSK injuries which included both lower and upper extremity injury in this study. This may also account for lack of identifying sex-dependent relationships on outcomes or covariates as biological sex differences [223], sex-dependent associations [224-226], sex-dependent recovery from injury [224-226], and importantly sex-dependent symptomologies [226-

228] have been previously identified in the context of concussion injury. As such future research examining long-term effects of SRC and/or MSK injury should consider these appropriately, potentially through stratifying MSK injury by upper and lower extremity and SRC injury through persistent symptoms as may be captured through validated devices like the Sport Concussion Assessment Tool symptom evaluation [215, 216]. Additionally, as time loss from injury had no association with any PA behavior, it may be warranted for future research to consider a time loss requirement for 'significant' injury longer than ≥ 7 days time loss.

5.6 Conclusions

Adults ages 18-33 with a history of adolescent sport-related injury in our study participated in MVPA, LPA, MPA, and VPA for a similar length of time daily and rate of bouts to those without significant injury history. A focus for healthcare practitioners for physically active adolescents should be continuing to ensure that they receive appropriate return to play and return to sport support after sports-related injury. Heterogeneity of SRC injury should be considered in future long-term SRC research.

5.7 Tables

Table 1. Sex-Cohort Specific Descriptive Statistics for Outcomes and Covariates

	SRC		MSK		UC	
	Male	Female	Male	Female	Male	Female
Age, mean (SD)	23.7(3.9)	23.7(3.5)	24.4(4.0)	23.6(3.8)	23.5(4.3)	22.0(3.2)
Time since, mean (SD)	8 (6-11)	8 (6-11)	8 (6-10)	8 (6-10)	-	-
Time loss, median (IQR)	14 (7-28)	14 (7-30)	36 (21-60)	40 (21-63)	-	-
MVPA, minutes (SD)	56.63 (29.08)	50.43 (19.10)	56.52 (24.98)	51.30 (26.16)	49.58 (16.99)	50.32 (25.34)
Light PA, minutes (SD)	206.24 (62.86)	207.43 (54.86)	192.97 (61.55)	194.97 (62.69)	188.36 (60.24)	196.85 (60.88)
Moderate PA, minutes (SD)	51.17 (24.51)	47.50 (16.83)	51.87 (21.91)	46.85 (22.28)	47.34 (15.27)	47.78 (23.55)
Vigorous PA, minutes (SD)	5.50 (11.55)	2.93 (4.36)	4.64 (6.99)	4.45 (7.13)	2.24 (3.60)	2.54 (3.72)
Sedentary, minutes (SD)	565.55 (83.03)	549.48 (85.75)	555.17 (99.07)	551.53 (69.13)	566.09 (95.29)	546.38 (71.03)

**Movement behavior outcomes are displayed as mean daily minutes; sport related concussion (SRC) cohort, musculoskeletal injury (MSK) cohort, uninjured control (UC) cohort.*

Table 2. Incidence Rate Ratios and 95% Confidence Intervals for Sedentary and Moderate-to-Vigorous Physical Activity Bouts

	Male			Female		
	IRR	95%CI		IRR	95%CI	
SRC						
MVPA bouts	0.87	0.62	1.22	0.87	0.62	1.22
MVPA bouts/1-minute MVPA	0.015	0.011	0.022	0.015	0.010	0.021
Sedentary bouts	14.22	13.08	15.45	12.39	11.29	13.60
Sedentary bouts/1-minute sedentary	0.025	0.023	0.027	0.023	0.021	0.025
MSK						
MVPA bouts	1.06	0.76	1.48	1.01	0.71	1.44
MVPA bouts/1-minute MVPA	0.019	0.013	0.026	0.020	0.014	0.028
Sedentary bouts	14.41	13.15	15.78	14.25	12.98	15.64
Sedentary bouts/1-minute sedentary	0.026	0.024	0.028	0.026	0.024	0.028
UC						
MVPA bouts	0.84	0.54	1.31	0.89	0.63	1.24
MVPA bouts/1-minute MVPA	0.017	0.011	0.026	0.018	0.013	0.025
Sedentary bouts	15.18	13.67	16.86	13.68	12.56	14.91
Sedentary bouts/1-minute sedentary	0.027	0.024	0.030	0.025	0.023	0.027

**Sex-cohort raw moderate-to-vigorous (MVPA) and sedentary bout IRRs and 95%CIs are equal to sex-cohort mean number of daily bouts, respectively; one bout is equal to 10 or more minutes of continuous MVPA time; sport related concussion (SRC) cohort, musculoskeletal (MSK) injury cohort, uninjured control (UC) cohorts.*

Table 3. Regression Modelling for All Physical Activity Intensities by Covariate

	Beta	P-value	95%CI	
Moderate-to-Vigorous PA				
Cohort				
SRC Injury (relative to UC)	3.16	0.464	-5.34	11.65
MSK Injury (relative to UC)	4.04	0.376	-4.93	13.01
Sex (Male relative to Female)	4.11	0.252	-2.95	11.17
Age (every one-year increase)	-0.35	0.552	-1.52	0.81
Time Since (every one-year increase)	0.27	0.745	-1.39	1.94
Time Loss (every one-day increase)	-0.004	0.826	-0.04	0.03
Light Activity				
Cohort				
SRC Injury (relative to UC)	14.93	0.145	-5.19	35.05
MSK Injury (relative to UC)	0.71	0.947	-20.55	21.97
Sex (Male relative to Female)	-4.40	0.604	-21.13	12.32
Age (every one-year increase)	2.48	0.078	-0.28	5.24
Time Since (every one-year increase)	-0.30	0.882	-4.23	3.64
Time Loss (every one-day increase)	-0.01	0.807	-0.10	0.08
Moderate Activity				
Cohort				
SRC Injury (relative to UC)	1.44	0.702	-5.98	8.86
MSK Injury (relative to UC)	2.08	0.602	-5.76	9.92
Sex (Male relative to Female)	3.09	0.324	-3.08	9.26
Age (every one-year increase)	-0.36	0.490	-1.37	0.66
Time Since (every one-year increase)	0.46	0.532	-0.99	1.91
Time Loss (every one-day increase)	-0.01	0.642	-0.04	0.03
Vigorous Activity				
Cohort				
SRC Injury (relative to UC)	1.76	0.094	-0.37	3.88
MSK Injury (relative to UC)	1.83	0.098	-0.44	4.09
Sex (Male relative to Female)	0.86	0.396	-1.15	2.86
Age (every one-year increase)	-0.04	0.801	-0.39	0.30
Time Since (every one-year increase)	-0.19	0.442	-0.69	0.31
Time Loss (every one-day increase)	0.005	0.477	-0.01	0.02

**moderate-to vigorous physical activity (MVPA; daily minutes), light physical activity (LPA; daily minutes), and moderate physical activity (MPA; daily minutes): complete-case multiple linear regression; vigorous physical activity (VPA; daily minutes): generalized linear modelling with gamma distribution and logarithmic link.*

Table 4. Multiple Linear Regression Complete Case Analysis for Sedentary Time by Covariate

	Beta	P-value	95%CI	
Cohort				
SRC Injury (relative to UC)	-1.00	0.946	-30.21	28.21
MSK Injury (relative to UC)	-7.92	0.639	-41.14	25.30
Sex (Male relative to Female)	10.28	0.399	-13.70	34.25
Age (every one-year increase)	-0.31	0.877	-4.28	3.66
Time Since (every one-year increase)	3.73	0.193	-1.90	9.36
Time Loss (every one-day increase)	0.07	0.295	-0.06	0.20

**Sport related concussion (SRC) injury history, musculoskeletal (MSK) injury history, uninjured control (UC).*

Table 5. Poisson Regression Complete-Case Models for Daily MVPA and Sedentary Bouts by Covariate

	IRR	P-value	95%CI	
MVPA Bouts				
Cohort				
SRC Injury (relative to UC)	0.93	0.703	0.64	1.35
MSK Injury (relative to UC)	1.19	0.350	0.82	1.74
Sex (Male relative to Female)	1.10	0.546	0.81	1.48
Age (every one-year increase)	0.95	0.063	0.90	1.00
Time Since (every one-year increase)	1.06	0.125	0.98	1.13
Time Loss (every one-day increase)	1.00	0.565	1.00	1.00
MVPA Bouts with MVPA Minutes Exposure				
Cohort				
SRC Injury (relative to UC)	0.85	0.410	0.59	1.24
MSK Injury (relative to UC)	1.08	0.669	0.75	1.57
Sex (Male relative to Female)	1.02	0.893	0.75	1.38
Age (every one-year increase)	0.96	0.115	0.91	1.01
Time Since (every one-year increase)	1.05	0.164	0.98	1.13
Time Loss (every one-day increase)	1.001	0.502	0.999	1.002
Sedentary Bouts				
Cohort				
SRC Injury (relative to UC)	0.92	0.078	0.84	1.01
MSK Injury (relative to UC)	0.98	0.700	0.89	1.08
Sex (Male relative to Female)	1.09	0.019	1.01	1.18
Age (every one-year increase)	0.99	0.305	0.98	1.01
Time Since (every one-year increase)	1.00	0.902	0.98	1.02
Time Loss (every one-day increase)	1.00	0.012	1.00	1.00
Sedentary Bouts with Sedentary Minutes Exposure				
Cohort				
SRC Injury (relative to UC)	0.92	0.075	0.84	1.01
MSK Injury (relative to UC)	0.99	0.892	0.90	1.09
Sex (Male relative to Female)	1.07	0.064	1.00	1.16
Age (every one-year increase)	0.99	0.348	0.98	1.01
Time Since (every one-year increase)	0.99	0.553	0.98	1.01
Time Loss (every one-day increase)	1.0003	0.063	1.0000	1.0007

**Poisson regression completed with daily MVPA (minutes) or sedentary minutes person-time exposure, respectively, to examine bouts while controlling for daily minutes; one bout ≥ 10 minutes; IRR estimates reflect rate change to # bouts/day by covariate; sport related concussion (SRC) injury history, musculoskeletal injury history (MSK), uninjured control (UC).*

Chapter 6. Conclusion

The purpose of the SHRed Consequences of Concussion cohort study was to examine the long-term effect 5–15-year SRC injury history may have on a myriad of health-related outcomes as a paucity of long-term research has been identified [15, 20]. Knowing this, a lack of identifying any differences in outcomes of interest in this thesis for those with sport-related injury history relative to the uninjured may only suggest that the analytical approach to the data collected be reprised exhaustively and limitations addressed appropriately before concluding that truly no differences exist between injury cohorts and UC.

The results from Chapter 4 support the notion that it is plausible for young adults (ages 18-33) with a 5–15-year history of SRC or MSK injury sustained during adolescent (ages 11-18) sport participation to have body compositions comparable to uninjured controls who also participated in adolescent sport. This is evidenced by DXA scan measured fat masses and lean masses, indexed by height through FMI and LMI, and adjusted by sex, age, time since injury, and time loss from injury being no different for those with SRC or MSK injury history relative to uninjured controls. Similarly, the results from Chapter 5 suggest that these same young adults with SRC or MSK injury history engage in PA behaviors comparable to uninjured controls. This was evidenced by daily minutes of MVPA, LPA, MPA, VPA, and both daily MVPA and daily sedentary bout rates, all objectively measured through Actigraph accelerometers, being no different for MSK or SRC cohorts relative to the uninjured.

Overall, individuals with 5-15-year SRC or MSK adolescent injury history did not differ from uninjured controls when examining body composition or physical activity behaviors as young adults (ages 18-33). Only expected sex differences were observed regarding body composition and both time since injury and time loss from injury showed no associations with any outcomes of interest. The aggregate results from Chapters 4 & 5 are highly encouraging in a sport medicine and kinesiology realm as they may suggests that individuals with sport-related injury history may reap the same benefits from engaging in healthy PA behaviors as those without injury history. Additionally, as heightened adiposity levels are an independent risk factor for a several negative health outcomes, including generalized mortality, healthcare professionals managing the treatment of adolescents with sport-related injuries should focus on ensuring these individuals appropriately and effectively return to sport and/or play as findings from this thesis suggest adiposity levels may remain comparable to those without injury history. However, these findings are not completely congruent previous research examining lower extremity MSK injury where daily PA levels were lower and adiposity measures were higher for the injured relative to controls [29, 36, 207]. It is possible that awareness regarding the benefits of sport participation as well as recovery trajectories for those with SRC [229, 230] or MSK [231, 232] injury being improved with appropriate PA may have resulted in those with injury history in this thesis engaging in healthier lifestyles. This may suggest that the limitations of the studies conducted within this thesis need to be explored, and perhaps other factors need be considered when examining these data.

All results within this thesis were stratified by sex and analytical approaches were designed to allow for detection of sex differences. Covariate interaction with sex was also assessed in all statistical models within Chapters 4 & 5. No interaction terms were significant and retained in any models for PA behavior- or adiposity-related outcomes. Sex-dependent differences were identified when validating algorithms used to define PA intensities [Troiano (2011) and Freedson VM3 (2008)], where males were observed to score higher amounts of MVPA during a controlled laboratory exertional test. This may reflect poorer agreement of these algorithms with HRR-defined CSEP guidelines for males relative to females. The algorithms being validated through agreement with CSEP guidelines both did a poor job of accurately capturing PA intensities. This may simply reflect the reality that both of these algorithms were designed with flat track-walking data for use in free-living environments [119, 124] that the laboratory-performed BCTT failed to emulate through nominal but progressive increases in movement intensity via inclination. However, relative to each other, both algorithms appeared comparable. Biological sex differences were also identified in FMI and LMI values and were consistent with previous literature, where females tend to have higher FMI and lower LMI relative to males [166].

Covariates of interest across all analyses also included age, time since initial injury, and time loss from injury. While initial literature review suggested that age and time since initial injury might reflect time required for injuries to heal, as well as the potential for psychosocial and physiological change correlated with age, the only association identified was between age and LMI, where one-year increases in age resulted in an increase in LMI. No association between age or time since initial injury and any other outcomes of interest within this thesis were identified. Literature review suggested that time loss from injury could potentially correlate to injury severity, thus allowing for injury severity to be examined quantitatively in a retrospective analysis. However, no associations between time loss from injury and any outcomes of interest within this thesis were identified.

6.1 Strengths

Strengths of this thesis and the SHRed Consequences of Concussion study outcomes begin with the size and design of the study. Based on previous research, the analyses included in this thesis were powered to detect differences as little as 10-minutes of daily MVPA [95, 208] between injury groups, with 10-minutes being typically considered a clinically meaningful amount [78, 208]. Additionally, about half the participants from the SHRed Consequences of Concussion cohort study were recruited based on pre-existing knowledge of injury history and injury severity, adding validity to injury classification(s) and reducing possibility of misclassification bias. This thesis represents a small part of a massive recruitment effort (nearly 5,000 attempts to contact via phone call and word of mouth recruitment methods) from a trained team utilizing a scrutinous screening interview (Appendix E), resulting in a promisingly reliable population of study. Adding to this, both PA behavior and body composition outcomes were objectively measured through previously used and validated methods of ActiGraphy [29, 124, 195, 196] and DXA scanning [36, 146, 233], respectively. Thus, the results discussed in this thesis show promising internal and external validity. This thesis and the SHRed Consequences of Concussion cohort study sought to fill an identified gap in existing literature in the context of potential long-term sequalae of sport-related concussion [15, 20] and discussed results take large steps to fill these gaps as well as identify more granular and appropriate direction for future research. As more aspects of the larger study end and results to fruition, a reliable and validated multifaceted picture of the long-term health of an individual with SRC or MSK injury history will emerge.

6.2 Limitations

Limitations respective to each manuscript within this thesis are discussed in each chapter. Overall, examination of long-term injury history utilizing retrospectively collected injury information subjected results from Chapters 4 and 5 to recall bias. This was plausibly nondifferential between cohorts and the primary research questions involving comparison of SRC and MSK injury history to UC was likely unaffected. However, in the context of defining an injury as 'significant' to classify an individual into one of three cohorts, there may be concern for this recall bias as failing to accurately report time loss from injury 5 to 15 years ago and being off by as little as a day could differentially classify an individual. However, this only applies to those not recruited through previous cohort study involvement where this information was validated.

Selection bias posed through recruitment of individuals from primarily word of mouth or previous cohort study involvement was addressed through sensitivity analysis respective to Chapters 4 or 5, where no association between recruitment source and outcomes of interest were identified. Selection bias may also include interpreting what kind of individual voluntarily participates in a study assessing PA outcomes and body composition. It may be proposed that recruitment for the SHRed Consequences of Concussion cohort study attracted interest and participation from more athletically inclined individuals that are more habituated to participating in healthy PA behaviors. While FMI and LMI outcomes placed the average individual inside normal ranges for each respective index [166], individuals as a whole well-surpassed PA behavior levels previously identified in Canadian populations [95] as well as Canadian guideline recommended weekly levels of MVPA and LPA [129]. This may suggest results from this study are only generalizable to previously and currently active individuals with PA levels non-representative of the Canadian general population. The discrepancy in findings from this thesis relative to previous research may be due to these prior studies examining MSK injury history [29, 36, 207] are described by significant (requiring intervention) MSK lower extremity injuries and suggests the current findings may not have completely accounted for the heterogeneity of

MSK injuries. In this, heterogeneity of SRC risk, presentation, and recovery [15, 48, 170, 182, 214, 234-236] was also not appraised and no stratification of injuries occurred within either SRC or MSK injury cohorts. While these discussed limitations may prove to be important considerations for analyses of the same data and future research, the aggregate findings of adults with 5-15-year SRC or MSK adolescent injury history having PA behavior and body composition outcomes similar to those without injury history, while falling within normal ranges/exceeding guideline recommendations, is highly encouraging.

6.3 Future Research Directions

Given the limitations consistently discussed in Chapters 4 & 5, future research examining body composition and PA behaviors in young adults with long-term sport-related injuries should involve addressing the heterogeneity of SRC and MSK injuries. For MSK, this may involve examining upper and lower extremity injuries distinctively and possibly specific injury types [e.g., ACL [36], ankle [237, 238]], and for SRC this may involve examining persistent concussion symptoms and concussion-like symptoms in the previously uninjured. Comparisons between body composition and PA behaviors should also be made to examine if associations exist where expected, as well as providing an opportunity to dispel suspicions of observer bias with regards to accelerometer-measured PA levels. Research utilizing a retrospective design quantifying both injury history and time loss from injury may benefit from including a robust definition of 'significant injury', through increasing the time loss requirement beyond the 7 days included within this thesis. This may help ensure that time loss from injury a) truly reflects injury severity 5-15 years later, and b) may reduce the likelihood of recall bias differentially misclassifying injury histories. Given the lack of differences between cohorts identified in this thesis, more thorough examination of individuals with 5–15-year injury history is warranted as findings do not suggest that longer-term sequalae of SRC injury may exist. Lastly, data and results from this thesis should be compared to other arms of the SHRed Consequences of Concussion study, where physiological, clinical, psychosocial, and neurodevelopmental outcomes are also to be interpreted in order to examine individuals with sport-related injury comprehensively through a multifaceted approach. Outcomes of interest may include cardiorespiratory fitness and further examination of body composition (physiological), symptom and concussion-like symptom presentation (clinical), and sport participation, primary sport withdrawal, and overall quality of life outcomes (psychosocial).

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Appendix

Appendix A

Linear Regression Model for Fat Mass Index by Covariate Adjusting for Recruitment Source

	Beta	P-value	95%CI	
Cohort				
SRC Injury (relative to UC)	0.056	0.373	-0.068	1.332
MSK Injury (relative to UC)	-0.058	0.419	-0.198	1
Recruitment Source	-0.049	0.350	-0.152	0.823
Sex (Male relative to Female)	-0.348	<0.001	-0.448	-0.248
Age (every one-year increase)	0.003	0.729	-0.014	0.140
Time Since (every one-year increase)	0.011	0.344	-0.012	0.099
Time Loss by Cohort				
SRC (relative to UC)	0.001	0.246	-0.001	0.001
MSK (relative to UC)	0.001	0.117	-0.001	0.002

**Sport-Related Concussion (SRC), Musculoskeletal (MSK), Uninjured Control (UC); word of mouth recruitment relative to previous cohort study recruitment.*

Linear Regression Model for Lean Mass Index by Covariate Adjusting for Recruitment Source

	Beta	P-value	95%CI	
Cohort				
SRC Injury (relative to UC)	0.783	0.005	0.234	1.332
MSK Injury (relative to UC)	0.376	0.236	-0.248	1
Recruitment Source	0.365	0.118	-0.093	0.823
Sex (Male relative to Female)	3.125	<0.001	2.680	3.569
Age (every one-year increase)	0.063	0.107	-0.014	0.140
Time Since (every one-year increase)	-0.003	0.947	-0.106	0.099
Time Loss by Cohort				
SRC (relative to UC)	0.002	0.189	-0.001	0.005
MSK (relative to UC)	0.003	0.162	-0.001	0.008

Sport-Related Concussion (SRC), Musculoskeletal (MSK), Uninjured Control (UC); word of mouth recruitment relative to previous cohort study recruitment

Appendix B

Regression Modelling for All PA Adjusting for Word of Mouth versus Previous Cohort Recruitment

	Beta	P-value	95%CI	
Moderate-to-Vigorous Physical Activity				
Cohort				
SRC Injury (relative to UC)	4.20	0.334	-4.35	12.76
MSK Injury (relative to UC)	5.27	0.253	-3.80	14.33
Sex (Male relative to Female)	4.88	0.176	-2.21	11.98
Age (every one-year increase)	-0.38	0.523	-1.54	0.78
Time Since (every one-year increase)	0.21	0.803	-1.45	1.87
Time Loss (every one-day increase)	0.00	0.812	-0.04	0.03
Recruitment Source	5.305	0.112	-1.25	11.86
Light Physical Activity				
Cohort				
SRC Injury (relative to UC)	14.53	0.162	-5.87	35.05
MSK Injury (relative to UC)	0.24	0.982	-21.37	21.97
Sex (Male relative to Female)	-4.70	0.584	-21.62	12.32
Age (every one-year increase)	2.49	0.077	-0.28	5.24
Time Since (every one-year increase)	-0.27	0.892	-4.22	3.64
Time Loss (every one-day increase)	-0.01	0.81	-0.10	0.08
Recruitment Source	-2.026	0.799	83.89	13.61
Moderate Physical Activity				
Cohort				
SRC Injury (relative to UC)	2.36	0.533	-5.11	9.84
MSK Injury (relative to UC)	3.16	0.432	-4.76	11.08
Sex (Male relative to Female)	3.77	0.232	-2.43	9.97
Age (every one-year increase)	-0.38	0.462	-1.39	0.63
Time Since (every one-year increase)	0.40	0.583	-1.04	1.85
Time Loss (every one-day increase)	-0.01	0.628	-0.04	0.02
Recruitment Source	4.674	0.109	-1.05	10.40
Vigorous Physical Activity				
Cohort				
SRC Injury (relative to UC)	1.84	0.147	-0.65	4.32
MSK Injury (relative to UC)	2.11	0.116	-0.53	4.74
Sex (Male relative to Female)	1.11	0.288	-0.95	3.17
Age (every one-year increase)	0.00	0.989	-0.33	0.34
Time Since (every one-year increase)	-0.19	0.428	-0.68	0.29
Time Loss (every one-day increase)	0.00	0.524	-0.01	0.01
Recruitment Source	0.631	0.514	-1.27	2.54

**Recruitment source reflects word of mouth relative to previous cohort study recruitment sources*

Appendix C

Actigraph Distributions by Cohort

Cohort	Not Given	Given	Excluded	Included
	Total = 268		Total = 248	
SRC	8 (3.0%)	94 (35.1)	18 (7.3%)	76 (30.7%)
MSK	6 (2.2%)	78 (29.1%)	14 (5.6%)	64 (25.8%)
UC	6 (2.2%)	76 (28.4%)	13 (5.2%)	63 (25.4%)

Appendix D. Ethics Approval (Updated May 2024)

Conjoint Health Research Ethics Board
Research Services Office
2500 University Drive, NW
Calgary AB T2N 1N4
Telephone: (403) 220-2297
chreb@ucalgary.ca

CERTIFICATION OF INSTITUTIONAL ETHICS APPROVAL

Ethics approval for the following research has been renewed by the Conjoint Health Research Ethics Board (CHREB) at the University of Calgary. The CHREB is constituted and operates in compliance with the *Tri-Council Policy Statement: Ethical Conduct for Research Involving Humans* (TCPS 2); Health Canada Food and Drug Regulations Division 5; Part C; ICH Guidance E6: Good Clinical Practice and the provisions and regulations of the Health Information Act, RSA 2000 c H-5.

Ethics ID:	REB21-0548_REN3
Principal Investigator:	Carolyn Emery
Co-Investigator(s):	Deborah Marshall Bradley Gordon Goodyear Lianne Tomfohr James Preston Wiley Chantel Debert Keith Yeates Jonathan Smirl Daniel Kopala Sibley Jeffrey Dunn Tyler Cluff Patricia Katherine Doyle-Baker Brian Brooks Sean Dukelow Ashley Harris Kathryn Schneider Gillian Currie
Student Co-Investigator(s):	Courtney Kennedy Matthew Neill Olivia Galea Kirsten Holte Lauren Miutz Benjamin Leggett Joseph Carere Jacalyn Moore Delowar Hossain Joel Burma

	Heather Shepherd
Study Title:	Surveillance in High School and Community Sport to Reduce Concussions and their Consequences
Sponsor:	University of Calgary National Football League's Scientific Advisory Board Alberta Innovates - Health Solutions Canada Research Chairs Secretariat University of Calgary

Effective: 7-May-2024 **Expires:** 7-May-2025

Restrictions:

This Certification is subject to the following conditions:

1. The research as described in the application is approved.
2. Proposed modifications must be approved prior to implementation.
3. An application for renewal must be made annually.
4. Closure requests must be submitted when the research is complete or terminated.

Approved By:	**Date:**
Kathleen Oberle, PhD, Vice-Chair, CHREB	22-Apr-2024 4:32 PM

Note: This correspondence includes an electronic signature (validation and approval via an online system).

Appendix E. Invitation and Screening Interview

Invitation and Screening Interview

Hi, this is *insert your name* I am calling on behalf of Dr. Carolyn Emery from the Sport Injury Prevention Research Centre at the University of Calgary. May I speak with *insert participants full name*?

General Population Participants:

We are contacting you because you contacted us to receive information about participation in our study. Do you have time now to discuss the study? (If yes, continue. If no, ask when a good time would be to call back).

Previous Study Participants:

If person answering phone states that individual no longer lives at family residence confirm that person being spoken to is parent, if not request to speak with participant's parent. When speaking with parent explain purpose of call as follows: Some time ago your child participated in a Sport Injury Prevention Research Centre research study. We are grateful for the time they spent participating. We currently have a new study starting soon and will assess the longer-term consequences of sport-related injuries. We wanted to contact your child to see if they would be interested in participating. Do you think it would be possible to leave contact details for the study coordinator with you to pass on to your child? Alternately if your child agrees, we could contact them directly. (If person agrees to pass on study details, provide details. Alternately if parent preference is for study team to contact child once consent for parent to pass on child's new number to research team has been given by child, arrange a time to call back to get participant's new number. Once call is complete thank the individual for their time and end call, otherwise thank the individual for their time and end call).

Alternately if participant is reached on initial call continue as follows: Some time ago you participated in a Sport Injury Prevention Research Centre research study. Thanks again for your time participating. We currently have a new study that is starting soon, and we wanted to contact you to see if you would be interested in participating. Do you have time now to discuss the study? (If yes, continue. If no, ask when would be a good time to call back. If not interested, thank the individual for their time and end call).

Last time you participated, our study was focused on the prevention of injuries. We are now evaluating any longer-term consequences of sport-related injuries.

All Participants:

Participation in the study will require you to complete some online questionnaires, perform a sport concussion assessment test virtually and then if possible given current COVID-19 restrictions attend in person at the University of Calgary and Foothills Medical Centre for further testing. In-person testing involves use of clinical and functional tools that measure balance, eye movement, the neck, and hand-eye coordination. To examine your fitness and daily activity levels you will also complete an exercise test and wear an activity monitor afterwards. A full body X-ray will be performed to examine your overall muscle and fat mass, and finally an MRI will be used to collect information about your brain. Imaging as well as potentially some of the eye hand coordination and blood flow/ heart rate testing is performed at a separate time at the Foothills Medical Centre. There will be no cost to you to participate in the study. Does this sound like something you would be interested to take part in? (If yes, continue. If no, thank the individual for their time and end call).

To include you in this study we would need to ensure that you're eligible to participate. There are a few questions I will ask you over the phone. Is that OK? (If yes, continue. If state not enough time now, arrange a good time to call back). Most of the questions are related to your general health to make sure that it is ok for you to participate.

CONCUSSION (SRC) PARTICIPANT.

First could you please briefly describe any sport-related CONCUSSION injuries you have had when you were 18 years old or younger that was assessed by a healthcare professional or that resulted in time loss from sport of >1 week *(for previous study participants, this will be any concussion as a youth since the study)*. Did this injury happen 5 or more years ago? Please describe any medical attention you received for it as well.

Could you also please describe any concussion injuries you have had as an adult? Did any of these occur within the last 12 months?

Secondly could you please tell me if you have experienced any musculoskeletal injury which resulted in time loss from sport/school/work/ADL >1 week?

NO CONCUSSION INJURY PARTICIPANT (MSK and HC groups)

Could you please tell me if you have experienced a CONCUSSION?

MUSCULOSKELETAL INJURY (MSK) PARTICIPANT.

Could you please briefly describe any sport-related MUSCULOSKELETAL INJURIES you have had when you were 18 years old or younger that resulted in time loss from sport of >1 week *(for previous study participants, this will be any MSK injury as a youth since the study)*. Did this injury happen 5 or more years ago? Please describe any medical attention that you received for it as well.

Could you also please describe any MSK injuries you have had as an adult that resulted in time loss from sport/school/work/ADL's >1 week? Did any of these occur within the last 12 months?

HEALTHY CONTROL (HC) GROUP

Have you had a MSK injury in the past which resulted in time loss from sport/school/work/ADL's > 1 week?

ALL POTENTIAL PARTICIPANTS

Are you pregnant?
Yes – they will be excluded from participating.

Have you ever been diagnosed with any of the following?

- Bone fracture, arthritis or other muscle or bone condition?
- Systemic disease
- Respiratory condition
- Circulation or heart problem
- Neurological disorder
- Vestibular or balance disorder
- Whiplash or neck pain of traumatic or non-traumatic origin
- Significant psychiatric disorder

If the participant answers no to everything above, they will be eligible to participate in the study.

If the participant answers yes to any of the above, further detail will be sought to determine eligibility.

- From what I can tell it appears that you are eligible to participate in the study.
- The next step is to explain how we are collecting data for the study. Things are a bit different now because of COVID-19.
  Firstly, we will send an invitation to your phone to create an account on RedCap the website we use to provide you with information you will need for the study. Once you have generated your account you will be able to access a more detailed description of the testing procedures as well as a section for you to provide your consent to participate. Once you submit this, you will be able to access a range of questionnaires through your account. You will complete these first after which we will do the SCAT virtually. You might remember this measure from the Hockey study. It consists of a series of questions looking at memory function as well as a symptom scale and some balance measures. Following completion of the SCAT virtually, and if COVID -19 restrictions still allow for it, you will come in for testing at the Sport Injury Prevention and Research Centre at the University of Calgary and also attend the Foothills Medical Centre, Calgary for the MRI.
- The next step is going to be figuring out what is the best time for you to complete the virtual SCAT and then come in for testing after you complete this and the online component. Remember that the time for testing in person may need to change.
- The way I usually go about this is I will read through what we have for options for the virtual SCAT assessment and then in person testing. If any times stand out as workable let me know and we will book you in. I can also send you a list of dates and times so you can look it over with your schedule and get back to me. You will just need to make sure you have completed the online component before we do the virtual SCAT.

Once a testing time is booked

- I will send you a confirmation email that will outline the time, date, location etc. It will have a link to a map as well as directions regarding parking, what to wear etc. If for some reason there are some question you have that the online information and email does not address please let me know.
- Do you have any other questions? Thank you for your time, we'll be sending you an email shortly and be in touch with you just before the virtual SCAT and in person testing days. Goodbye.

Appendix F. Participant Consent Form

CONSENT FORM

TITLE: SHRed Concussions and their Consequences in Youth Sport (Surveillance in High School and Community Sport to Reduce Concussions and their Consequences)

FUNDING: Canada Research Chair in Concussion (PI C Emery), Canadian Institutes for Health Research Foundation Grant (PI C Emery)

INVESTIGATORS

Dr. Carolyn Emery PT PhD (PI), Dr. Olivia Galea PT PhD (postdoctoral fellow), Dr Keith Yeates PhD, Dr. Kathryn Schneider PT PhD, Dr. Jonathan Smirl PhD, Dr Brian Books PhD, Dr. Daniel Kopala Sibley PhD, Dr. Chantel Debert MD MSc, Dr. Ashley Harris PhD, Dr. Bradley Goodyear PhD, Dr. Jeff Dunn PhD, Dr. Lianne Tomfohr-Madsen PhD, Dr. Sean Dukelow MD PhD, Dr. Tyler Cluff PhD, Dr. Deborah Marshall PhD, Dr. Gillian Currie PhD, Dr. Patricia Doyle-Baker PhD, Dr. Jean-Michel Galarneau, Dr. Delowar Hossain, Ms. Lauren Miutz, Mr. Joel Burma, Mr. Joseph Carere, Ms. Courtenay Kennedy, Ms. Kirsten Holte, Ms. Melanie Scholz, Mr. Ben Leggett, Ms. Carolyn Graham, Ms. Emily Faris.

This consent form is only part of the process of informed consent. It should give you the basic idea of what the research is about and what your participation will involve. If you would like more detail about something mentioned here, or information not included here, please ask. Take the time to read this carefully and to understand any accompanying information. You will receive a copy of this form.

BACKGROUND

Sport related concussions are among the leading sport and recreation-related injuries experienced by youth and account for over 50% of all youth concussions in Canada. Concussion can have longer-term consequences in some individuals leading to absence from sport, school and work. Persistent symptoms following concussion may include headaches, dizziness, neck pain, limitations in concentration, reduced exercise capacity, altered eye motion, mood difficulties, and increased health care resource use. Although short-term effects of concussion have been investigated in youth, little is known regarding potential longer-term consequences. Further knowledge regarding potential long-term consequences of concussion will inform a better understanding of factors influencing recovery and potential treatment strategies. There is a critical need for research examining longer-term health outcomes following concussion. You have been asked to participate in this study as you may have experienced a sport-related concussion or other injury in your youth, or because you participated in sport in your youth and did not sustain any significant injury. 300 participants are expected to participate in this study.

WHAT IS THE PURPOSE OF THE STUDY?

The purpose of this study is to determine whether or not youth and young adults with a history of sport-related concussion or injury in the past 5-15 years differ in symptoms, concentration, brain function, physical performance, body composition, exercise capacity, activity levels, neck function, balance, eye motion, mood, and utilization of health care resources compared to youth and young adults with no history of injury.

WHAT WOULD I HAVE TO DO?

If you choose to participate in the study you will undergo a short phone interview (10-15 minutes) with research team member to determine if you are eligible and willing to consent to participate in the study. Testing will take place in the Sport Injury Prevention Research Centre (Faculty of Kinesiology) and Calgary Foothills Medical Centre (imaging only). After you have agreed to receive information about the study, you will be sent a link by email to the SHRed Consequences of Concussion website portal which provides access to the consent form and questionnaires for you to complete. You will need a secure internet connection and your own computer/phone to complete the consent form and questionnaires. Questionnaires will be related to mood and/or symptoms of anxiety, depression, and subjective quality of life. The baseline questionnaire contains questions related to sex and gender identity, sexual orientation pre-existing medical conditions, and health care utilization including hospital stays. The questionnaires and cognitive task measure (Cambridge Brain Sciences) will take approximately 90 minutes to complete and will include:

1. Baseline questionnaire (demographics, sport participation, healthcare utilization, medical history)
2. Cambridge Brain Science Neurocognitive Assessment including 12 cognitive tasks designed to examine your concentration, thinking, and memory.
3. PROMIS Cognitive Function - Abilities Short Form 8a
4. Godin Leisure-Time Physical Activity Questionnaire (GLTPAQ)
5. Fatigue Severity Scale (FSS)
6. Insomnia Severity Index (ISI)
7. PROMIS Sleep Related Impairment questionnaire
8. EuroQol 5 Dimension Questionnaire (EQ-5D-5L)
9. The Personal Health Questionnaire – 9 (PHQ-9)
10. Generalised Anxiety Disorder 7 (GAD-7)
11. Athletic Identity Measurement Scale (AIMS)
12. Exercise Identity Scale (EIS)
13. Headache Impact Test (HIT-6)

You will also be asked to complete some assessment components virtually over Zoom (Sport Concussion Assessment Tool 5 (SCAT5) – see 6a below) following which you will be scheduled to come into the Sport Injury Prevention Research Centre, Faculty of Kinesiology, University of Calgary for a testing session, which will be approximately 2-hours in length (if COVID 19 restrictions allow). You will be provided with precise directions and appointment times that suit yourself and the researchers. Upon arrival at the Faculty of Kinesiology (Sport Medicine Centre entrance, 376 Collegiate Blvd, Calgary), you will be met by a researcher who will provide you with a parking pass and instructions for parking. You will then be asked to participate in a variety of functional and clinical tests. Testing components will include:

1. Height, weight, and waist circumference.
2. Dual-energy X-ray absorptiometry scan (DEXA): For the scan you will be asked to lay flat on an exam table while the arm of a machine passes over you from head to toe to

measure your fat and muscle mass. This test is an x-ray. It will take about 10 minutes and should not give you any discomfort. If you are pregnant at the time you will not be eligible for the DEXA study.

3. KINARM testing: This test uses robot technology to examine different elements of body awareness and thinking. For these tasks you will sit at the KINARM robot and grasp the robotic arms in order to perform a series of tasks while watching a scene projected onto a two-dimensional virtual reality display.
4. Funtional Gait Assessment (FGA). This test will require you to perform a series of 10 tasks while walking a short distance and examines performance of each of these individually to obtain a total score. Tasks to perform while walking include turning your head left and right, or up and down, walking quickly and slowly etc.
5. *Walking While Talking Test* requires you to walk a short distance while performing simple and more difficult mental tasks.
6. Clinical tests
    a. *Sport Concussion Assessment Tool 5 (if not already completed online)* involves completing a symptom scale and performing a series of mental and balance tasks such as walking along a line on the floor with a heel-toe walking style or balancing in different stances with your eyes closed. Your neck will also be briefly examined.
    b. *Head Thrust Test* involves the examiner holding your head while you are seated and quickly moving it to the left and right while you try to maintain focus of your eyes straight ahead.
    c. *Dynamic Visual Acuity and Gaze Stability Testing* involves sitting on a chair at a distance from the wall/ a computer screen and reading aloud a series of letters presented on a chart or the screen. This is done with your head still and also while the examiner moves your head side to side in time to a beat.
    d. *Vestibular Oculo-Motor Screening* involves a series of tests where you will be asked to move your eyes in certain directions while reporting on any symptoms these movements may cause. You will perform these tests in sitting mostly, with one test requiring you to stand and rotate your trunk right to left at a moderate pace.
    e. *Cervical Flexion Rotation Test* is performed with you lying on a medical bed. The examiner will lift your head as far as it can go (or as far as is comfortable) and gently turn it to the right and left. The test will not be performed if your neck is too sore to tolerate full range of motion.
    f. *Cervical Flexor Endurance Test* will be performed with you lying on a medical bed. You will be asked to lift your head off the pillow and then hold in this position for as long as you can tolerate while maintaining the same position, and not letting your head lower back down onto the bed.
    g. *Cervical Extensor Endurance Test* involves lying on the medical bed on your stomach. You will position your head over the edge of the bed so that it is unsupported. You will hold this position as long as you can manage without letting your head lower down toward the floor. This test may cause mild discomfort in your neck muscles related to fatigue.
    h. *Cervical Flexor, Extensor and Anterolateral Strength Test* involves you sitting or lying on the medical bed. In this position you will then be asked to resist a moderate to maximal force applied to different areas of your head for short durations. This

will be repeated three times at each location. You will be given a short rest between each repetition.

i. *Cervical Joint Position Error* is performed in sitting. You will wear a low-energy laser on your head with the beam focused on a target 90cm in front of you. With your eyes closed you will be asked to find certain positions on the target.

j. *Head Perturbation Test* is performed in sitting. The examiner will apply small amounts of pressure with their finger 3 times in random sequence to different parts of your head. You will be asked to resist each pressure applied and the test will be scored based on how well you are able to do this.

k. *Cervical Spine Manual Assessment* is performed with you lying on your stomach. The examiner will examine the joints in your neck by pressing gently downwards along the back and sides of your spine from the base of your skull to the top of your shoulder on the right and the left. You will be asked to report how each joint feels as it is pressed.

7. Aerobic fitness test (aproximately 8-12 minutes): Prior to completion of the test, you will be asked to complete a Physical Activity Readiness Questionnaire (PARQ+), a screening test to ensure that you have no contraindications to completing an aerobic fitness test. For this test, you'll be asked to cycle on a bike for as long as you can. While you are cycling the resistance on the bike will be increased. The test ends when you can no longer keep cycling, are too out of breath or fatigued, or experience an increase in symptoms beyond an acceptable amount. Before, after and for each minute during the test you will be asked to rate your sysmptoms. For each minute you will also be asked to rate your level of effort. During the test you will also be asked to wear a heart rate monitor (electrocardiogram, attached to your chest using small adhesive electrodes), a cap on your head like a swimming cap (fitted with light-emitting diodes, and an ultrasound to measure different nervous system functions such as blood flow to your brain), and a small tube on your finger (to measure your blood pressure).

   NOTE: PLEASE LET US KNOW IF YOU HAVE AN ALLERGY TO ADHESIVES. IF SO, THE HEART RATE MONITOR MAY NEED TO BE MODIFIED TO ONE NOT REQUIRING THE USE OF ELECTRODES. ALSO, FOR ELECTROCARDIOGRAPHY MEASUREMENTS, SELECTED SPOTS ON YOUR CHEST MAY HAVE TO BE SHAVED AND SLIGHTLY ABRADED TO APPLY THE MEASUREMENT SENSORS.

8. Activity Monitor: You will be asked to participate in a physical activity monitoring assessment using an accelerometer device (ActiGraph GT3x, GT9x). Specifically, you will be asked to wear small, lightweight devices attached via an elastic belt around your waist, and via a wrist strap to your wrist for a period of 7 days.

You will be asked also to participate in magnetic resonance imaging (MRI) at the Foothills Medical Centre.

9. You will be asked to undergo a one-hour magnetic resonance imaging (MRI) session at the Foothills Medical Centre. This is to help examine structure and function of your brain. Scientists look for the presence of brain biomarkers that may inform brain function and can be identified by the scan. Only one series of MRI scans will be done by a medical professional skilled in performance of MRI who will also complete the

standard safety screening with you to ensure MRI is a suitable technique. For example, MRI may be inappropriate for you if you are pregnant, have certain metal objects (e.g., braces) inside your body, or are too claustrophobic to enter the scanner. The MRI scan will require you to lie on your back inside an MRI scanner for about 40 minutes while scans of your head are performed. You will be holding a button, and if you are uncomfortable for any reason you can push the button to communicate with a technician. If you cannot lie still enough for us to perform a high-quality scan, are uncomfortable or anxious while in the MR scanner, or you want to stop for any reason you can be removed from the scanner immediately. You will not be given a sedative or injected with any intravenous contrast material.

WHAT ARE THE RISKS?
There are no expected risks associated with participating in this study. The in-person measurements described above will be done under close supervision and every effort will be made to ensure your safety. As with any physical activity there is the possibility of a muscle pull or strain, or soreness the next day from the endurance tests. Additionally, some of the tests of concentration or for neck and eye function or balance may result in you feeling mild symptoms such as dizziness, headache, nausea, or mental fog. These symptoms usually subside quickly once the test is complete and you may discontinue any test at any time. The risk of injury will be reduced by careful supervision during the testing procedures. Although you will only be asked to complete an aerobic fitness test following screening (PAR-Q+), it is possible that you may have symptoms of light headedness or nausea and this test can be discontinues at any time.

As some of the research activities will be completed in-person, it is important to recognize any risks that may be associated with the COVID-19 pandemic. When participants are visiting the Faculty of Kinesiology, University of Calgary for these research activities, there may be some additional risks, including:

- Increased exposure to other people (i.e., lab personnel)
- Risks associated with travel (i.e., public transit)

The research team will take all precautions, including the following, to mitigate the possibility of transmission:

- Use of secure remote communication methods
- COVID19 screening for study participants and study personnel before attending in-person research activities
- Use/provision of personal protective equipment for research participants and study personnel (i.e., masks, gloves)
- Provision of hand sanitizer for research participants and study personnel
- Single use research apparatus where possible (e.g., paper pillow and medical bed face hole covers)
- Sanitization of surfaces and multi-use equipment between participants
- Physical distancing measures of at least 2 metres whenever possible

The estimated dose of radiation from the DEXA scan is less than 25 mrads. No amount of radiation is completely safe. For the sake of comparison, the dose from a chest x-ray is 25 mrads, from a dental x-ray is 750 mrads, natural living at sea level exposes you to 100 mrads and watching TV one hour per day exposes a person to 1 mrad per year. The actual health risks from exposure to low x-ray doses are difficult to determine.

Magnetic resonance (MR) is a technique that uses magnets and radio waves, not radiation, to take pictures of the body. MRI has no known harmful effects if you have none of the risk factors, which you will be screened for in the pre-MRI screening interview. Specifically, you should not have an MRI if you have a pacemaker or certain other metal objects inside your body, especially around the eyes, because the strong magnets in the MR scanner might cause these to heat up or move, causing harm. You will also need to remove all metal from your clothing and pockets; otherwise, these objects could be pulled into the magnet and cause harm. No metal can be brought into the magnet room at any time since the magnet is always "on".

Transcranial Doppler ultrasound measures the speed of blood flow in deep brain blood vessels and uses sound waves to do so. Functional near-infrared spectroscopy measures the amount of oxygen within the blood in the outer regions of the brain and uses light to do so. These measures are commonly used in research and do not utilize radiation for image collection.

There may be some initial discomfort wearing the physical activity monitor and belt. However, the belt is fully adjustable to fit the individual and minimize any discomfort. It may be necessary to shave where the ECG electrodes are attached to your chest. It might take a few weeks for your hair to grow back at these spots.

In case of medical emergencies, standard Faculty of Kinesiology protocols will be followed which include calling Campus Security (403-250-5333) and 911 if required.

WHAT IF RESEARCHERS DISCOVER SOMETHING ABOUT ME?
In the unlikely scenario that a researcher observes a suspected abnormality in your results (i.e., images), a study physician will be consulted who will decide of the potential significance to your health. If considered potentially clinically relevant, you will be informed and recommendations for follow-up will be made.

I consent for the researchers to share findings with me:

☐ YES
☐ NO

ARE THERE ANY BENEFITS?
If you agree to participate in this study, there may or may not be a direct medical benefit to you. It is unlikely that your risk of experiencing any long-term difficulties in relation to your SRC will decrease because of participating in the study. However, the information we get from this study may help us to provide better injury management and prevention in the future through adolescent programs and sport. You will receive information about your cognitive tasks (Cambridge brain Sciences), body mass index, bone mineral density, % fat and lean body mass, aerobic fitness, neck, balance, and oculomotor function as well as the results of your MRI. If you are experiencing any persistent symptoms following your SRC these results may be useful to identify which modes of treatment might be helpful to you.

DO I HAVE TO PARTICIPATE?
No, you do not have to participate. Participation is completely voluntary, and you may withdraw from the study at any time by contacting the Research Coordinator. If you withdraw from the study, you may request to withdraw your data from the study. Please be advised that you will not be able to withdraw your data once data analysis has begun. Data collected in person will usually be analyzed within one week of collection.

Continued participation should be as informed as your initial consent, so feel free to ask for clarification or new information throughout your participation. If there is new information available throughout this study period, you will be informed as soon as possible.

WILL I BE PAID FOR PARTICIPATING, OR DO I HAVE TO PAY FOR ANYTHING?
Participants will not be paid to participate in the study and there will be no costs to the participants. Parking at both the Sport Injury Prevention Research Centre and Calgary Foothills Medical Centre will be provided to you.

WILL MY RECORDS BE KEPT PRIVATE?
All the information collected will remain strictly confidential. Your privacy will be assured. Only the investigators responsible for this study, the research assistants who will be doing the assessments and data analysis, and the University of Calgary Conjoint Health Research Ethics Board will have access to your identifiable information. Confidentiality will be protected by using a study identification number in the database. Any results reported from the study will in no way identify study participants.

REDCap is a web-based electronic data capture (EDC) solution with servers located under Canadian jurisdiction. All data are encrypted and stored directly on its servers. Researcher access to the survey data is a combination of role-based access, strict password management processes, and two-factor authentication. Survey responses cannot be linked to your computer. Test results for the Cambridge Brain Science cognitive assessment completed via the REDCap platform is collected under your unique identification number.

IF I SUFFER A RESEARCH-RELATED INJURY, WILL I BE COMPENSATED?
If you suffer an injury as a result of participating in this research, the Sport Injury Prevention Research Centre, the University of Calgary or the Researchers will provide no compensation to you. You still have all your legal rights. Nothing said in this consent form alters your rights to seek damages.

SIGNATURES
Your signature on this form indicates that you have understood to your satisfaction the information regarding your participation in the research project and agree to participate as a participant. In no way does this waive your legal rights nor release the investigators or involved institutions from their legal and professional responsibilities. You are free to withdraw from the study at any time without jeopardizing your health. If you have further questions concerning matters related to this research, please contact:

Research Coordinator at 403-220-3394 or Dr. Carolyn Emery (Primary Investigator) at 403-220-4608

If you have any questions concerning your rights as a possible participant in this research, or research in general, please contact the Chair of the Conjoint Health Research Ethics Board, University of Calgary, at 403-220-7990. The University of Calgary Conjoint Health Research Ethics Board has approved this research study (REB21-0548).

If appropriate, a research coordinator may contact you about other opportunities to participant in related research projects. Additional ethics approval from a Research Ethics Board will be obtained for any future studies. Your decision to participate in these related projects will not in any way influence or affect your involvement in this study.

☐ By checking this box, I agree to be contacted about opportunities to participate in related research projects.

By checking this box and typing my name below, I am electronically signing this consent form.

☐ I agree to participate in this study.

Name

Appendix E. Baseline Medical History Survey

Baseline Medical History

Adding new Record ID **2542**

Event Name: **Event 1**

Record ID 2542

CONCUSSION HISTORY

Have you ever had a concussion (either diagnosed or not) or been "knocked out" or had your "bell rung"?
* must provide value

○ Yes ○ No

reset

INJURY HISTORY

In addition to concussions listed above, have you had any injury requiring medical attention OR at least 1 day missed participation from sport or physical activity?
* must provide value

○ Yes ○ No

reset

Do you have any ongoing injuries?
* must provide value

○ No
○ Yes
○ Do not know
○ Refuse to answer

reset

Are you currently taking medication for ANY injuries?
* must provide value

☐ No
☐ Yes, ibuprofen (e.g. Advil)
☐ Yes, acetaminophen (e.g. Tylenol)
☐ Yes, other

MEDICAL HISTORY

Have you ever been diagnosed by a physician with any of the following?
(Check any that apply)
* must provide value

☐ Bone fracture, arthritis, or other muscle or bone condition?
☐ Systemic disease (e.g. cancer, thyroid disease, heart disease)?
☐ Respiratory condition (e.g. asthma, chronic respiratory failure, congenital lung abnormalities)?
☐ Circulation or heart problem (e.g. murmur, congenital deformity, irregular beat)?
☐ Neurological disorder (e.g. cerebral palsy, pinched nerve, "stinger", MS)?
☐ Sleep disorders (e.g. sleep apnoea, narcolepsy, restless leg syndrome, insomnia)?
☐ Vestibular or balance disorders (e.g. benign paroxysmal positional vertigo, Meniere's disease, labyrinthitis, migraine associated vertigo)?
☐ Whiplash or neck pain of traumatic or non-traumatic origin that required treatment or medical intervention (e.g. referral to GP, frequent use of pain-relieving medication, physiotherapy, chiropractic)?
☐ None

Have you ever experienced headaches? * must provide value	◯ Yes ◯ No reset
Does anyone in your family experience headaches? * must provide value	◯ Yes ◯ No reset
Have you ever been concerned that you may have an attention or learning issue? * must provide value	◯ Yes ◯ No reset
Have you ever been diagnosed by a health care professional with any of the following? (Check any that apply) * must provide value	☐ Cognitive delay ☐ Communication Disorder ☐ Persuasive development disorder ☐ ADHD ☐ Learning disability ☐ Anxiety disorder ☐ Disruptive behaviour disorder ☐ Oppositional defiant disorder ☐ Mood disorder ☐ Depression ☐ Bi-polar disorder ☐ Developmental Coordination Disorder ☐ Other ☐ None
Do you have a family history of any of the following neurodegenerative diseases? * must provide value	☐ Dementia ☐ Parkinson's disease ☐ Alzheimer's Disease ☐ Other ☐ None
Are you currently taking medications? * must provide value	◯ No ◯ Yes ◯ Don't know ◯ Refuse to answer reset e.g. inhaler, Tylenol, antidepressants, birth control
Are you currently taking supplements? * must provide value	◯ No ◯ Yes ◯ Don't know ◯ Refuse to answer reset e.g. vitamins, minerals, protein powder

HEALTH CARE UTILIZATION

Please indicate if, in the past 12 months, you have visited the following practitioners or received the following services (exclude visits/services as an inpatient)

Physician - emergency room
* must provide value

- ◯ No visits
- ◯ Visited
- ◯ Refuse to answer

reset

Physician - family
* must provide value

- ◯ No visits
- ◯ Visited
- ◯ Refuse to answer

reset

Physician - sport medicine
* must provide value

- ◯ No visits
- ◯ Visited
- ◯ Refuse to answer

reset

Physician - surgeon
* must provide value

- ◯ No visits
- ◯ Visited
- ◯ Refuse to answer

reset

Physician - other specialist
* must provide value

- ◯ No visits
- ◯ Visited
- ◯ Refuse to answer

reset

Physician - other specialist
* must provide value

- ◯ No visits
- ◯ Visited
- ◯ Refuse to answer

reset

Physician - other specialist
* must provide value

- ◯ No visits
- ◯ Visited
- ◯ Refuse to answer

reset

Physician - other specialist
* must provide value

- ◯ No visits
- ◯ Visited
- ◯ Refuse to answer

reset

Nurse Practitioner
* must provide value

- ◯ No visits
- ◯ Visited
- ◯ Refuse to answer

reset

Neuropsychologist
* must provide value

- ◯ No visits
- ◯ Visited
- ◯ Refuse to answer

reset

Psychologist
* must provide value

◯ No visits
◯ Visited
◯ Refuse to answer

reset

Counsellor
* must provide value

◯ No visits
◯ Visited
◯ Refuse to answer

reset

Physiotherapist
* must provide value

◯ No visits
◯ Visited
◯ Refuse to answer

reset

Chiropractor
* must provide value

◯ No visits
◯ Visited
◯ Refuse to answer

reset

Registered massage therapist
* must provide value

◯ No visits
◯ Visited
◯ Refuse to answer

reset

Athletic therapist
* must provide value

◯ No visits
◯ Visited
◯ Refuse to answer

reset

Dietician
* must provide value

◯ No visits
◯ Visited
◯ Refuse to answer

reset

Bracing or Orthotics
* must provide value

◯ No visits
◯ Visited
◯ Refuse to answer

reset

Magnetic resonance imaging (MRI)
* must provide value

◯ No visits
◯ Visited
◯ Refuse to answer

reset

Computer tomography (CT scan)
* must provide value

◯ No visits
◯ Visited
◯ Refuse to answer

reset

Radiographs (x-rays)
* must provide value

◯ No visits
◯ Visited
◯ Refuse to answer

reset

Other * must provide value	◯ No visits ◯ Visited ◯ Refuse to answer reset
In the past 12 months, have you been admitted to the hospital for any reason? * must provide value	◯ Yes ◯ No reset
Apart from any hospitalizations listed above, have you EVER been admitted to hospital for a significant health condition? * must provide value	◯ Yes ◯ No reset
Drug Use	
During the last 12 months, did you use any illicit or non-prescription drugs? * must provide value	◯ No ◯ Yes ◯ Prefer not to answer reset
If yes, please indicate the drugs used: * must provide value	☐ No drug use ☐ Crack/cocaine ☐ Pot/marijuana ☐ LSD/Hallucinogens ☐ Heroin/Opiates ☐ Speed/Stimulants ☐ N/A, no other drug use ☐ Unknown ☐ List other drugs ☐ Prefer not to answer
Alcohol Use	
During the past month, have you had at least one drink of any alcoholic beverage such as beer, wine, wine coolers, or liquor? * must provide value	◯ No ◯ Yes ◯ Prefer not to answer reset
During the past month, how many days per week or per month did you drink any alcoholic beverages, on the average? * must provide value	
A drink is 1 can or bottle of beer, 1 glass of wine, 1 can or bottle of wine cooler, 1 cocktail, or 1 shot of liquor. On days when you drank, about how many drinks did you drink on the average? * must provide value	
Considering all types of alcoholic beverages, how many times during the past month did you have five or more drinks on an occasion? * must provide value	

Appendix F. Participant Actigraph Wear-Time Daily Survey

Date form completed

This is hidden from the survey and auto-populates with the date and time the survey was opened, based on the users device time and date

[ ] Y-M-D H:M:S

Today's Date [ ] Today Y-M-D

1:00pm = 13:00	5:00pm = 17:00	9:00pm = 21:00
2:00pm = 14:00	6:00pm = 18:00	10:00pm = 22:00
3:00pm = 15:00	7:00pm = 19:00	11:00pm = 23:00
4:00pm = 16:00	8:00pm = 20:00	12:00pm = 24:00

Last night I went to bed at [ ] Now H:M

Last night, How long did it take you to fall asleep? [ ] Minutes

Last night, Did you take any medication to help you sleep? ○ Yes ○ No reset

How many times did you wake-up last night? [ ]

I woke-up this morning at: [ ] H:M

This morning, I got out of bed at: [ ] H:M

Rate the quality of your sleep from 1-10

○ 1 (Worst Sleep Ever)
○ 2
○ 3
○ 4
○ 5
○ 6
○ 7
○ 8
○ 9
○ 10 (Best Sleep Ever)

reset

Did you take a nap yesterday?

○ Yes
○ No

reset

Did you take the Actigraph off yesterday?

○ Yes
○ No

reset

What *COLOUR* Actigraph did you wear during the *DAY* yesterday?

○ Red ○ Black

reset

Where **did you wear your actigraph during the *DAY* yesterday?**

○ Waist ○ Wrist

reset

What *COLOUR* Actigraph did you wear during the *NIGHT* yesterday?

○ Red ○ Black

reset

Where **did you wear your actigraph during the *NIGHT* yesterday?**

○ Waist ○ Wrist

reset

Please use the textbox to provide any comments or notes about wearing the Actigraphs yesterday or about completing this form.

Expand

Coordinator/RA comments

Expand

How/when was this log completed?

Prospectively - Paper = Completed on paper by participant but entered into the redcap by study staff

Retrospectively - On their own = They completed the log using the survey link but Completion Date/Time ≠ Today Date

Retrospectively - Researcher Assisted = Research spoke with participant to complete the logs after the fact

◉ Prospectively-Survey Link
○ Prospectively-Paper
○ Retrospectively-On Their Own
○ Retrospectively-Researcher Assisted

reset