ANALYSIS OF POST-CONCUSSION SLEEP QUALITY IN YOUTH

OBJECTIVE POST-CONCUSSION SLEEP QUALITY: EXPLORING THE EFFECTS OF CONCUSSION AND DETERMINING ITS RELATIONSHIP WITH RECOVERY OUTCOMES IN CHILDREN AND ADOLESCENTS

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A Thesis Submitted to the School of Graduate Studies

In Partial Fulfillment of the Requirements for

the Degree Master of Science in Rehabilitation Sciences

MASTER OF SCIENCE (2020)	McMaster University
(Rehabilitations Science)	Ontario, Canada
TITLE:	Objective post-concussion sleep quality: exploring the effects of concussion and determining its relationship with recovery outcomes in children and adolescents.
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NUMBER OF PAGES:	xii, 128

Lay Abstract

Children and adolescents are at risk for experiencing changes in sleep following concussion that result in poor sleep quality. Given the important role of sleep in maintaining our overall health, sleep likely plays a role in recovery. However, this relationship is poorly understood. The purpose of this dissertation is to identify how sleep changes following concussion and how these changes affect sleep quality and recovery. Study results reveal that the sleep parameters in the initial 4 weeks following concussion are significantly affected by concussion, suggesting that the sleep quality of children and adolescents is poorer than healthy youth. However, sleep quality does appear to improve with time. Further analyses found sleep quality does not appear to be related to recovery length or outcomes. Thus, the sleep quality of youth may be negatively impacted by concussion, but this may not directly influence recovery.

Abstract

Background: Sleep is commonly disrupted following pediatric concussion. Recently, post-concussion sleep quality has been identified as a potential factor that may influence recovery length. However, few studies have examined this relationship using objective sleep measures in a pediatric population. Nor, have any studies examined the trajectory of objective sleep parameters after pediatric concussion.

Objectives: The purpose of this thesis is to**:** 1) Provide a review of current literature regarding pediatric concussion, healthy sleep quality, and sleep quality in the context of concussion and recovery from concussion; 2) Examine how objective sleep outcomes are affected and change post-concussion in children and adolescents; 3). Explore how post-concussion sleep quality parameters are related to length of recovery, quality of life (QOL), and depression symptomatology; and 4) Discusses the results from the two studies in the context of current literature and of each other.

Methods: Sleep quality was inferred from the outcomes of five objective sleep parameters. Sleep parameters were measured using actigraphy in children and adolescents with concussion following return to school (RTA) and return to activity (RTA) protocols. Sleep data during the initial 4 weeks of recovery was assessed as an outcome, as a predictor of recovery length, and as a correlate of quality of life (QOL) and depression symptomatology

Results: Most objective post-concussion sleep quality parameters were adversely affected by concussion but show trajectories indicating improvement throughout the initial 4 weeks of recovery. Sleep quality parameters were not associated with time to complete return to school or activity protocols. Sleep parameters were not strongly correlated with QOL or depression symptomatology outcomes.

Conclusions: These results indicate that objective post-concussion sleep quality is impaired following concussion, but these outcomes do not appear to be associated with recovery, QOL or depression symptomatology. Other factors, or improvements in sleep quality may better explain recovery outcomes.

Acknowledgements

I have enjoyed my chance to work with the wonderful colleagues and faculty who make up the Rehabilitation Science Program. I would like to take the opportunity to thank everyone who encouraged the success and completion of this thesis.

Firstly, I would like to express my sincere gratitude for my supervisor Dr. Carol DeMatteo who provided me with this opportunity. Her support, and encouragement allowed me to push through doubt or lack of motivation to keep me going. Under her supervision and guidance, I have learned to become a better researcher and critical thinker.

I would also like to thank my committee members. Dr. Catherine Wiseman-Hakes was always available to offer her support and expertise when in need. Her insight was invaluable and her questions challenged me to become a better researcher. Dr. Joyce Obeid allowed me to learn new applications that would provide the foundation for my thesis work. Dr. Obeid taught me to continue to be critical of my own work in order to improve its quality and strength.

Additionally, I would like to extend a sincere thanks to Dr. Paul Stratford, without who, I would still be trying to figure out my preliminary analyses. His insight allowed me to develop, understand, and then answer my research questions. Our friendly conversations always left me with the confidence to know that I was capable of figuring out anything out.

Lastly, I would like to thank my friends and family who supported me emotionally throughout my journey. I owe particular gratitude to my fiancé, Jocelyn Cameron, whose encouragement was instrumental in providing me with the confidence to succeed throughout this process.

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List of Abbreviations

RTS	Return to School
RTA	Return to Activity
PPCS	Persistent post-concussion symptoms
CDC	Center for Disease Control and Prevention
SE	Sleep efficiency
TST	Total Sleep Time
WASO	Wake after sleep onset
SOL	Sleep onset latency
NOA	Number of awakenings/arousals
AAL	Average Arousal Length
SD	Sleep disturbance
PSG	Polysomnography
PSQI	Pittsburgh Sleep Quality Index
PCSS	Post-Concussion Symptoms Scale
TBI	Traumatic brain injury
QOL	Quality of life
REM	Raid eye movement
KS-52	Kidscreen 52
CDI-2	Children’s Depression Inventory Version 2
95% CI	95% Confidence interval
Med.	Median
2^{nd}, 3^{rd} qrt	2^{nd} and 3^{rd} quartile
HR	Hazards ratio

Declaration of Academic Achievement

Michael Fisher is the primary author and contributor to this thesis. From September 2018 to September 2020, he was responsible for scoring actigraph data, organizing participant information, data analysis, interpretation of data, drafting manuscripts, and incorporating comments and feedback. Thesis supervisor, Carol DeMatteo, whom the original study data belonged to, was responsible for reviewing and refining research questions, study design, findings, and manuscripts. Dr. Catherine Wiseman-Hakes and Dr. Joyce Obeid were responsible for providing guidance and feedback throughout the completion of the thesis and at committee meetings. Dr. Wiseman-Hakes reviewed manuscripts and the completed thesis, providing feedback and comments for consideration. Dr. Joyce Obeid was responsible for training Michael Fisher in the methodology for scoring actigraphy data. Relevant information regarding participant information used in this thesis was pulled from REDCap by Sarah Randall and Jose Jakuboski.

CHAPTER ONE:

REVIEW OF RELEVANT LITERATURE

1.1 Concussion in Children and Adolescents

1.11 Concussion

A concussion is a traumatic brain injury caused by biomechanical forces due to impact, induced by any contact to the head or body that transmits a significant force to the brain. Following impact, concussion results in rapid functional disturbances in neurological function that typically resolves spontaneously over time (McCrory et al., 2017). The symptoms experienced by persons with concussion are often unique to the individual, in that, a person may experience any variety and combination of clinical symptoms (eg. cognitive, somatic, emotional symptoms), physical symptoms, cognitive impairment, balance impairment, or neurobehavioural changes (Piland et al., 2006). Immediate changes in sleep and wakefulness are also common following a concussion. Children and adolescents may experience some form of post-concussion sleep-wake disturbance, often resulting in either too much or too little sleep, daytime sleep dysfunction, or poor general sleep quality following a concussion (Cohen et al., 2009; Halsteand et al., 2018; Purcell, 2012).

While symptom presentation is often unique to the individual, concussion symptoms can result in chronic fatigue, difficultly concentrating, frequent headaches, sensitivity to noise and light, dizziness, and irritability (McCrory et al., 2017). These symptoms are often detrimental to the lives of children and adolescents, finding that concussion symptoms burden is associated with clinically meaningful impairments to cognitive, school-related, and overall health-related quality of life (Russell et al., 2019). Typically, most of these symptoms recover spontaneously with time. However, some concussion-related issues may persist well after expected recovery timelines in a sub-set of people (Babcock et al., 2013; Barlow et al., 2010; Eisenberg et al., 2013;

Grool et al., 2016; Zemek et al., 2016). This can present considerable challenges for children and adolescents which can affect aspects of their physical and psychological wellbeing (DeMatteo et al., 2014; Moran et al., 2012; Russell et al., 2019), as well as their mental health (Chrisman & Richardson, 2014; Emery et al., 2016; Kirkwood et al., 2001; Manley et al., 2017). Concussion should be treated as a serious injury and appropriate steps to manage the concussion and encourage complete recovery should be prioritized.

1.12 Epidemiology of Concussion in Youth

With increased societal awareness and education, concussion is now recognized as a major public health concern (Russell et al., 2011). Considering that youth under the age of 19 represent the majority of persons diagnosed with sport and recreationally related concussion (Baldwin et al., 2018), younger populations appear to be particularly at risk for experiencing a concussion. In North America, it has been found that concussion presents as one of the most common reasons that youth seek medical care (Guerriero et al., 2012; Meehan et al., 2011).

In Ontario alone, between 2008 and 2016, 1,330,336 people were diagnosed with concussion, averaging 147,815 cases per year. The reported annual incidence of concussion was found to be 1153 per 100 000 people, representing over 1% of the population (Langer et al., 2019). Here, children under 5 years old were found to have the highest incidence of concussion of all ages. Other studies focused on Ontario populations have found a 30% increase in the monthly rate of children presenting to the emergency department with concussion between the years 2009 and 2016, with this trend becoming especially apparent in females (Matveev et al., 2018). While the increasing rates of concussion may be explained in part by greater public recognition and likelihood to seek medical attention (Bakhos et al., 2010; Langer et al., 2019), these studies highlight the seriousness of the issue and importance for further research into youth concussion.

1.13 Recovery after Concussion

In order to ensure that youth are recovering from concussion, it is important to understand what the ‘normal’ or ‘expected’ timeline of recovery looks like in children and adolescents. The current consensus on concussion defines clinical recovery as the resolution of post-concussive symptoms along with the ability to resume participating in normal activities such as school, work, and sport (McCrory et al., 2017). This is meant to demonstrate that the individual has recovered in all domains that may be impaired after a concussion. While this definition provides a standard for assessing general clinical recovery it does not provide a criterion that would prove that an individual has undergone complete neurobiological recovery. As a result some individuals may have subclinical neurocognitive deficits even after they are no longer clinically symptomatic and are able to return to normal daily living (Williams et al., 2015). This is particularly dangerous, as these people still remain more vulnerable to additional head impacts (Bey & Ostick, 2009; Slobounov et al., 2007).

It appears as if the timeline for recovery from concussion is different for youth and adults. Previous literature has shown that most symptoms will improve and resolve spontaneously within the first 7 to 14 days post-injury, however, there is growing evidence to show that children require approximately 2 to 3 weeks longer to recover than adults (Davis et al., 2017; Field et al., 2003; Harmon et al., 2013; Hecimovich et al., 2018; McCrory et al., 2017; Purcell et al., 2016; Rose et al., 2015), and approximately 30% of youth are still symptomatic at one month (Zemek et al., 2016). As a result, the Berlin 5th Consensus Statement on concussion now acknowledges that the expected duration for symptoms recovery is approximately 4 weeks for children and adolescents (McCrory et al., 2017).

Return to School and Return to Activity Guidelines

With increasing evidence demonstrating the serious consequences associated with mismanaged concussion, greater efforts have been made to ensure that individuals are appropriately recovered before returning to their normal activities (DeMatteo et al., 2015; DeMatteo et al., 2015; McCrory et al., 2017). As a result, there has been a large push for the implementation of protocols that promote a structured return to school (RTS) and return to activity (RTA) for children and adolescents. With slightly varying adaptations of the Zurich or Berlin consensus guidelines (McCrory et al., 2013, 2017), these protocols provide sequential stages of recommendations that guide an individual through a step-wise, symptom based, management strategy in attempts to ensure that the individual reaches an adequate stage of recovery before returning to normal activity. Several RTS and RTA protocols have been produced and are recommended in the management of concussion in youth (DeMatteo et al., 2019; Halsteand et al., 2018; Lumba-Brown et al., 2018; McCrory et al., 2017).

RTS protocols revolve around progressively increasing a person's cognitive load in order to ease them back into the demands of school, whereas RTA protocols focus on progressively increasing one's level of physical activity to prevent re-injury while returning to preinjury activity, including competitive sport. Typically, RTS should be considered the primary focus of school aged children and adolescents (Iverson & Gioia, 2016; Purcell et al., 2019) and should precede completion of RTA protocols (DeMatteo et al., 2019). Each protocol can be completed relatively simultaneously, however, it is recommended that children be fully integrated back into school before returning to RTA stages involving high risk activity like competitive contact sport (DeMatteo et al., 2019).

The timeline to complete each protocol has been described by a few different studies. The likelihood of returning to activity over time was summarized in a study of 81 high school athletes by McKeon et al., 2013, where the probability of an athlete returning to play in 1 to 2 days was 2.5%, 71.3% for a 7 to 9 day return, and 88.8% for a 10 to 21 day return. However, there is a considerable amount of inter-study variation in how long participants take to complete each protocol. A strong description of protocol completion timelines comes from a prospective cohort study by DeMatteo et al., 2019, who examined 139 children ages 5 to 18 progressing through RTS and RTS protocols. Researchers found that the median time to complete RTS protocols was 35 days and the median time to complete RTA protocols was 38 days. However, in a retrospective cohort of 198 participants ages 8-17, Purcell et al., 2016 found that the median time to RTS and RTA was much shorter. Here, the reported median time to RTS was only 3 days and the median time to RTA was 20 days. Another study with a smaller sample size demonstrated that 50% of high school athletes returned to school by day 3, and that 50% of the athletes returned to play by day 13 (Chrisman et al., 2019). The discrepancies and variation in recovery timelines between these studies may be attributed to differences in protocol design and implementation, as well as variation between each studies inclusion and exclusion criteria.

While information from the 5th Consensus on concussion supports that each step in the protocol should take at-least 24 hours so that RTA protocol completion would take a minimum of 1 week (McCrory et al., 2017), there is still a limited consensus of the amount of time recommended to complete each protocol. The current understanding is that the progression through each of the stages is, and should continue to be, based uniquely on the individual and their own symptoms progression (DeMatteo et al., 2019; Rose et al., 2016). However, children frequently report experiencing concussion symptoms even after protocol completion (DeMatteo, Randall, et al., 2019). Thus, the need for more standardized concussion protocols in research and in practice may also be needed to ensure that all children return to school and activity safely.

1.14 Persistent Post-Concussion Symptoms and Prolonged Recovery

Following a concussion, a subset of children and adolescents will experience persistent post-concussion symptoms (PPCS). The current concussion consensus defines PPCS as any non-specific symptoms that persist beyond the expected clinical recovery time (McCrory et al., 2017). While the definition of "expected" recovery differs slightly in the literature, most studies define recovery within 4 weeks as 'normal' in children (Ayr et al., 2009; Daneshvar et al., 2011; Davis et al., 2017; McCrory et al., 2017; Zemek et al., 2016). Studies show that most children will recover from a concussion within this expected timeframe, however, upwards of 30% of children and adolescents will have symptoms continuing beyond the expected timeframe (Babcock et al., 2013; Barlow et al., 2010; Eisenberg et al., 2013; Grool et al., 2016; Zemek et al., 2016). Furthermore, some studies show that upwards of 11% are symptomatic at 3 months (Babcock et al., 2013; Barlow et al., 2010; Eisenberg et al., 2014), and approximately 2% are symptomatic beyond 1 year (Barlow et al., 2010).

Those with PPCS may endorse any array of concussion-like symptoms. Typically, the most commonly reported persistent symptoms in the literature appear to be headache, fatigue, and frustration (Babcock et al., 2013; Barlow et al., 2010; Blume et al., 2012; Eisenberg et al., 2014). Even symptoms that were not initially present in the acute stages of injury may develop over time. In a prospective cohort of adolescents and young adults, researchers found that forgetfulness, frustration, fatigue, and sleep disturbance commonly developed after the acute stages of recovery (Eisenberg et al., 2014). These PPCS can prolong the individual's recovery and can present significant life-challenges for children and adolescents, resulting in absences from school, poor academic performance, worsening mood, and loss of social activities, which collectively, may contribute to post-concussion depression and anxiety as well as lower quality of life (DeMatteo et al., 2014; Manley et al., 2017; Marsh et al., 2013; McCrory et al., 2017; Russell et al., 2019; Todd et al., 2018; Valovich McLeod et al., 2017; Yeates et al., 2012).

Predictors of Persistent Post-Concussion Symptoms and Prolonged Recovery

Research has shown that the recovery trajectory of youth and the likelihood of developing PPCS can be influenced by individual traits. While several possible factors have been hypothesized and tested, results often vary between studies. It is important to clarify this confusion and determine what specific risk factors reliably predict one's risk of PPCS and a longer recovery. By establishing risk factors and identifying them in individuals, clinicians may begin to predict and more appropriately manage or accommodate for at-risk persons.

The strongest evidence for identifying possible risk factors of PCSS and prolonged recovery comes from three recent, large-scale studies. The first of which is a systematic review of 101 articles by Iverson et al., 2017. The authors mention that the methodology and measured clinical outcomes differed between the studies used, but the most consistent predictor of delayed recovery was the initial severity of one's acute concussion symptoms. There was also evidence to suggest that development of subacute headaches or depression, issues with pre-injury mental health, female sex, and adolescence increased the risk for PPCS and delayed recovery. The second study by Zemek et al., 2016, examined 2006 children and adolescents ages 5 to 18 who presented to the emergency department following a concussion. In the risk score model, researchers found that the female sex, persons older than 13, having a prior history of migraine, concussion, and headache, as well as sensitivity to noise, fatigue, answering questions slowly, and 4 or more errors on the Balance Error Scoring System tandem stance were significant in predicting PPCS. This model was then validated in a cohort of 1057 participants to demonstrate the predictive strength of the identified risk variables. Lastly, in a 2019 study of 759 athletes ages

13 to 25, Marshall et al., 2019 found that female sex, age, and pre-morbid anxiety were significant in predicting the length of time from concussion to recovery. Drawing from shared themes across these studies, it appears that female sex, adolescent age, concussion history, initial symptom score, premorbid mental health, and headache/ migraine are consistent factors that influence the likelihood of PPCS and delayed recovery. Consideration of these factors in individuals may be important in the management of their concussion and post-concussion outcomes. However, none of these factors are modifiable. Future research should look to identify modifiable risk factors that can be acted upon in a clinical setting and can be targeted in concussion management strategies. Post-concussion sleep quality may be an appropriate target.

1.2 Sleep Trends in Children and Adolescents

1.21 Sleep Trends in the General Population

Sleep is not a passive or static state of neural activity, rather, it is a dynamic neural process comprised of several complex active stages and patterns involving several brain regions. These sleep and wake patterns are regulated by homeostatic and circadian processes that work naturally within a 24-hour cycle (Borbely, 1982)**.** The rhythmicity of this cycle is responsible for inducing sleepiness at night and wakefulness in the morning, allowing us to achieve an appropriate amount of sleep and function each day. These sleep-wake cycles are influenced by both by biological and social factors that can alter the timing, length, and quality of sleep (Blunden & Galland, 2014; Schmidt et al., 2012). Proper regulation and maintenance of sleep is needed for achieving physical, cognitive, emotional, and mental health. To appreciate the effects of concussion on sleep, it is important to first understand normal sleep trends in children and adolescents of the general public.

Sleep Trends in Healthy Children and Adolescents

In general, the Center for Disease Control and Prevention (CDC) recommends that 3 to 5 year-olds sleep 11 to 13 hours, 5 to 10 year-olds sleep 10 to 11 hours, and adolescents sleep 8.5 to 9.5 hours (CDC, 2010). In a study by Williams et al., 2013, these recommendations were tested in a large sample of the United States public to determine if these age populations were receiving the appropriate amount of recommended sleep. The sleep duration of 6776 children and adolescents from birth to age 18 was assessed using time diaries in 1997, 2002, and 2007 on two random days in September or May. The total median sleep times were estimated from the figures displayed and shown in **Table 1.** The researchers observed a continuous decrease in total sleep time from birth until age 16 with sleep trends that mirrored the recommendations made by the CDC. Researchers also found no clinically significant evidence of gender and racial/ethnic differences in age-conditional medians of sleep duration but did find that sleep duration was shorter during the week and longer on weekends for older children. Other literature provides evidence to support this week-day/weekend sleep discrepancy, finding that adolescents have greater variability in their sleep trends between weekends and week-days, likely attributed to demands imposed by school schedules (Merdand et al., 2014).

Similarly, in another large study of self-reported sleep duration in the United States, Maslowsky & Ozer, 2014 found that sleep time decreased from age 13 to 18, however estimates were lower than those reported by Williams et al., 2013 (results displayed in **Table 1**). Researchers also found that adolescent males slept statistically longer than females and white Caucasians slept longer than Hispanics, African Americans, and other races/ethnicities. Although, while statistically different, the differences in sleep between these group was never greater than 15 minutes and likely does not constitute a clinically meaningful difference.

Large amounts of information regarding sleep quality and normative sleep quantity trends using objective measurement is more sparse. A systematic review and meta-analysis of 87 studies (conducted in Northern America, Europe, Asia, Middle East, South America, and Oceania) that used actigraphy by Galland et al., 2018 provides the largest amount of normative objective sleep data in healthy children and adolescents. The average total sleep duration for different age groups are displayed in **Table 1**. The results of the of the study reveal that the average sleep duration for each age group is typically less than the sleep duration observed by Williams et al., 2013 and the recommendations made by the CDC. Although, consistent with the previous studies mentioned (Maslowsky & Ozer, 2014; Williams et al., 2013), results showed a decline in sleep duration with age and demonstrated significant differences in sleep duration between week-days and weekends in the older age groups. Researchers also reported the mean values of different sleep quality variables. For ages 3 to 18, the mean sleep onset latency (SOL) and wake after sleep onset (WASO) was 19 minutes and 55 minutes, respectively. For ages 3 to 14, the mean sleep efficiency (SE) was 86.3%. This estimate is consistent with what is generally considered a healthy SE in most literature (≥85%) (American Psychiatric Association, 2000; Landry et al., 2015; Reed & Sacco, 2016). The study did not provide information describing normal values for activity counts as well as the average length and number of awakenings.

2.22 Why Sleep Matters

It is well established that sleep has an important function in maintaining electrical and chemical balances that are essential for normal function (Banks & Dinges, 2007; Klumpers et al., 2015; Worley, 2018). Consequently, sleep plays a substantial role in how we function, where the quality of one's sleep is reflected in the way a person feels mentally, emotionally and physically (Chaput et al., 2016). Most frequently researched is the association between sleep and cognitive function. Consistent evidence demonstrates that poor sleep is associated with impaired cognitive performance, attention, and working memory (Alhola & Polo-Kantola, 2007; Durmer & Dinges, 2005). Literature suggests that brain areas involved in certain neurocognitive functions appear to be particularly sensitive to sleep loss and disturbance (Meehan et al., 2011). In children, sleep difficulties can be associated with academic difficulty and poor academic performance (Nevéus et al., 2007; Noland et al., 2009; Ohayon et al., 2000; Perez-Chada et al., 2007; Wiseman-Hakes et al., 2019). This is supported by observations found in a 2010 meta-analytic review which demonstrated that sleep quality, sleep duration, and daytime sleepiness were all significantly related to the performance of youth in school (Dewald et al., 2010).

A neurophysiological link between sleep and neuroplasticity has also been empirically demonstrated. Research finds that sleep, specifically the later stages of sleep, including slow wave sleep and rapid eye movement, are essential for long-term learning processes. In that, plastic changes that occur due to learning during wakefulness correspond with specific topographical changes in sleep that the alter cortical excitability to strengthen and reorganize synaptic connections which promote functional learning. Conversely, sleep deprivation induces changes that alter these mechanisms that impair neuroplastic changes needed for learning (Gorgoni et al., 2013). Because of this association, sleep is also though to have an important role in neurological changes that promote neurorecovery and functional learning after insult.

Sleep deprivation also appears to be bidirectionally implicated in a person's mood and mental health (Alvaro, Roberts, & Harris, 2013; Krystal, 2012). A study by Kouros & El-Sheikh, 2015 found significant associations between both objective and subjective sleep quality and disruptions in the mood of children. This study highlights an important connection between sleep and mood, providing evidence in support of a possible causal relationship between sleep issues and mental health outcomes in children. Furthermore, in a 2013 systematic review, researchers found that sleep impairment in adults was predictive of higher levels of depression and a depression/anxiety variable (Alvaro et al., 2013). This is not surprising considering that sleep disorders are often seen comorbidly with several mental health conditions.

This association also holds true for several physical health and pain-related conditions. Studies have shown that healthy people who report having sleep issues are more likely to be obese (Bell & Zimmerman, 2010; Cappuccio et al., 2008; Garaulet et al., 2011; Noland et al., 2009), have increased risk of cardiovascular disease (Nagai et al., 2010), have dampened endocrine and immune responses (Banks & Dinges, 2007), tend to endorse more general pain symptoms, and report more frequent headaches (Bruce et al., 2017; Dosi et al., 2015; Pecor et al., 2016; Song et al., 2018). Similarly, multiple studies have shown that healthy people tend to endorse more concussion-like symptoms at baseline if they self-reported poor sleep or were found that have objectively measured SD in previous nights (McClure et al., 2014; Stocker et al., 2017). Furthermore, evidence from reviews and a recent meta-analyses also reveal sleep is essential for optimal athletic performance in youth (Taylor et al., 2016; Watson, 2017) and that chronic lack of sleep is a risk factor for increased risk of injury in adolescents during activity (Gao et al., 2019; Milewski et al., 2014).

These studies provide strong evidence that implicate sleep quality in several aspects of short-term and long-term health. Consequently, some researchers call on health professionals to become more cognizant of these associations and push for greater clinical prescription of sleep interventions in certain cases of physical, psychiatric, and cognitive conditions (Medic et al., 2017).

2.23 Measuring Sleep Quality

Sleep quality is used as a broad subjective term that describes how well someone slept. In general, sleep quality lacks an established definition in the literature (Krystal & Edinger, 2008). The word quality itself is open for interpretation and can mean different things in different contexts. The definition of the quality of something is a subjective term that is inferred from other characteristics, be it subjective or objective. Only then by assessing each of these individual characteristics can you make an educated guess as to what that person's sleep quality was like. An important distinction to be made is between objective and subjective sleep quality. Subjective sleep quality is inferred from how well the person perceives their sleep. This constitutes questions such as, how easily they fell asleep, how refreshed the felt when they woke up, and if they felt like they got a sufficient amount of sleep. Usually a certain score on a subjective questionnaire determines how their sleep quality is interpreted. Objective sleep quality examines the sleep activity of a persons. Considering sleep measures such as, sleep duration, efficiency, fragmentation, and architecture. These outcomes are usually compared to normal estimates of healthy sleep behaviour to make an inference about the overall quality of their sleep.

Both forms of measurement assess different aspects of sleep quality and provide information about different characteristics of sleep. Studies have shown that there can be discrepancies between the inferred quality of a persons objective sleep and what they report subjectively about the quality of their sleep (Zhang & Zhao, 2007), even in children with concussion (Berger et al., 2017). While subjective and objective sleep are different, they are both important to consider. Therefore, one's interpretations of a person's sleep quality must be reflective of the measurement techniques applied (Shrivastava et al., 2014).

Assessing Sleep Quality after Concussion

There are several ways to measure sleep following a concussion. In the general assessment of concussion, most symptoms checklists will ask the individual a few questions regarding their sleep quality following the injury as part of a larger questionnaire. These checklists provide a quick means to determine if a person is experiencing any subjective forms of sleep disturbance (SD), but only provide a vague and limited idea of how sleep has been impacted. More in-depth measurement tools of sleep quality exist however, they are not often used clinically in the assessment of concussion but are more frequently used by researchers when addressing sleep-specific research questions (Mosti et al., 2016). Each sleep measure approximates sleep quality or sleep behaviour differently and can address a person's sleep either through objective or subjective means. Examples of commonly used sleep measures and the advantages and disadvantages of their use are shown in **Table 2.**

Objective Sleep Measurement: Polysomnography and Actigraphy

The gold standard for assessing objective sleep behaviour is polysomnography (PSG). PSG is a multiparametric test involving sleep clinicians and different measures of biological activity. During assessment, clinicians continuously monitor and measure brain wave activity, eye movement, muscle movement, heart rate, and respiratory patterns in order to examine sleep, sleep cycles, sleep architecture, and the structural organization of sleep-cycles. Clinicians can use this information to describe the quality of one's sleep, as well as identify, diagnose, and discriminate between sleep disorders. While PSG is considered to be the best measurement of sleep activity, its use in research is limited by the associated cost and time of assessment. In the context of research, this often results in smaller population sizes and limits the feasibility of repeated nightly observations. In addition, people may experience considerable night-to-night variation and evaluation in a foreign setting can result in a "first-night effect", which can significantly influence a person's sleep behaviour. As such, it is recommended that at-least two consecutive nights of assessment be performed (Newell et al., 2012). However, this may not always be feasible.

Alternatively, actigraphy can be used as another means to measure objective sleep activity. An actigraph is a small, portable device typically worn on the wrist or hip and is commonly used in sleep medicine as an effective way to monitor sleep behaviour outside of a sleep clinic. The device captures acceleration in three planes of motion (vertical, anteroposterior, and mediolateral) and uses a scoring algorithm to determine periods and characteristics of sleep and wakefulness (Sadeh, 2011). Actigraphy can be used in healthy children or used to identify insomnia, hypersomnia, circadian rhythm disorders, and sleep disturbances in children with chronic conditions (Ancoli-Israel et al., 2003; Morgenthaler et al., 2007; Sadeh, 2011). Unlike PSG, actigraphy offers a cheaper, less invasive assessment of sleep behaviour that can be conducted in the person's natural sleeping habitat, therefore eliminating laboratory effects and making repeated nightly observations more feasible (Ancoli-Israel et al., 2003). For these purposes, actigraphy was selected for this thesis to objectively assess post-concussion sleep parameters.

In an updated review of the usefulness of actigraphy, researchers found sufficient evidence to support the use of actigraphy in a healthy normal population, with most studies finding that actigraphy is a valid and reliably way to observe sleep and possesses strong sensitivity to detect periods of sleep (Sadeh, 2011). However, research supports that actigraphy-based measurement is significantly limited by poor specificity, in that studies comparing actigraphy scoring to PSG measures in children show strong agreement for the detection of periods of sleep but not for wakefulness (Meltzer & Westin, 2011). This results in erroneous classification of wakefulness during periods of high activity sleep and erroneous classification of sleep during periods of low activity wakefulness (Galland et al., 2014). The addition of supplementary tools such as sleep diaries can also be used in conjunction with actigraph assessment to increase the accuracy of detecting sleep and wakefulness patterns (Wickwire et al., 2016). With the combination of some form of sleep-tracking method, actigraphy is thought to provide a valid measure to detect various sleep disturbances (Sadeh, 2011) and appears to be a valid proxy for assessing sleep outcomes in concussed populations (Wickwire et al., 2016). A recent study examining the sleep-wake disturbances in patients with traumatic injuries found that actigraphy was a valid method of measuring night time sleep and wakefulness when compared with PSG (Bigué et al., 2020).

Objective Sleep Quality Variables of Sleep Quality

Sleep efficiency (SE) is commonly used to assess sleep quality when using actigraphy. SE quantifies the ratio between a person's total sleep time (TST) and their time in bed (expressed as a percentage), providing an overall, broad sense, of how well a person slept. SE is thought to relate more clearly to sleep quality than other than sleep variables because other sleep continuity measures of sleep and wakefulness are indirectly reflected in the calculation of SE (Åkerstedt et al., 1994). However, SE alone does not provide information regarding a persons wake and arousal behaviour during sleep (Shrivastava et al., 2014). For instance, a person may appear to have a high SE despite experiencing frequent but short periods of restless awakenings throughout the night, resulting in fragmented sleep and poor overall sleep quality. Without information regarding arousal behaviour, it is difficult to make inferences about a person's sleep architecture and how much deep sleep a person may have actually received (Shrivastava et al., 2014).

To accommodate for this limitation, considerations of sleep quality should also be collectively reflective of other measures of sleep quality. Measures such as TST, sleep onset latency (SOL), wake after sleep onset (WASO), which refers to the time spent awake after a person has fallen asleep, as well as information on the length and number of nighttime awakenings and arousals should be considered. These variables provide additional information about a persons arousal behaviour, allowing researchers to more appropriately infer about sleep fragmentation and a person's sleep architecture (Shrivastava et al., 2014a). Each of these measures describe a different component of one's sleep and contributes a piece of information that allows researchers to collectively assess overall sleep quality.

Scoring Algorithms

Different algorithms are used to convert raw actigraphy data into meaningful estimates of sleep and wake patterns. Motion is captured by the actigraph device, scored as a count. Software evaluates the count frequency within a specified epoch (a pre-determined short interval of time) and interprets the activity as a period of sleep or arousal based on the specific parameters set by the selected algorithm. The two most common algorithms used in actigraphy are the Sadeh (Sadeh et al., 1994) and the Cole-Kripke (Cole et al., 1992) algorithm. The Sadeh algorithm was initially validated against PSG in a sample of adults and adolescents, showing agreement rates in sleep-wake scoring between 91% and 93%. The Cole-Kripke algorithm was initially validated only in adults with approximately 88% agreement between sleep-wake identification when compared with PSG.

Since their initial validation, technological advancements have led to the development of newer actigraphy devices such as the GT3X+ (ActiGraph™; ActiGraph, Pensacola, FL, USA). However, little research has been done to compare these devices to PSG in order to comprehensively assess their validity. Only one study has addressed the validity of the GT3X+ in children and adolescents. In a small study of 13 school age children and teens and 22 adults, Quante et al., 2018 compared the sleep-wake estimates from the Sadeh and the Cole-Kripke algorithm to PSG. Both algorithms demonstrated reasonable agreement of sleep-wake estimation when compared with PSG (81-86%), with each algorithm demonstrating good sensitivity but poor specificity. The Sadeh algorithm was less sensitive to detect sleep (0.82-0.91) than the Cole-Kripke (0.88-0.96) but was more accurate in detecting wakefulness (Sadeh: 0.47-0.68; Cole-Kripke: 0.35-0.64). When compared to PSG, the GT3X+ using the Sadeh and Cole-Kripke algorithms measured TST with modest to strong accuracy (ICC = 0.64 and 0.88, respectively) but poorly estimated wake after sleep onset WASO (ICC = 0.00 and 0.10, respectively) and SE (ICC = 0.13 and 0.33, respectively). These results are consistent with similar studies that have examined the Sadeh and Cole-Kripke algorithm in adult populations. de Souza et al., 2003 found that both algorithms accurately identified 91% of all PSG epochs, again demonstrating high sensitivity (Sadeh: 97% agreement; Cole-Kripke: 99% agreement) but low specificity (Sadeh: 44%; Cole-Kripke: 34%). These results also demonstrated that both algorithms overestimated TST, SE, and SOL. Collectively, these results indicate that both scoring algorithms are comparable and are reasonably accurate when compared to PSG. However, both algorithms are poor in identifying periods of wakefulness (low specificity). Results from actigraphy measures should be interpreted with consideration of this limitation.

1.3 Sleep After Concussion

1.31 Incidence and Symptoms of Post-Concussion Sleep Disturbance

Sleep disturbance (SD) is a frequently identified issue and complaint in children and adolescents following traumatic brain injury (TBI) and concussion (Gagner et al., 2015). Post-concussion SD includes a wide variety of non-specific sleep-wake disruptions that are often unique to the individual and independent of the cause or severity of the injury (Morse & Kothare, 2018). SD can be classified into four categories: reduced sleep duration or continuity, sleep timing alterations due to circadian rhythm disorder, alterations in sleep architecture (i.e. sleep stages), and sleep pathology or sleep disorders (Sateia, 2014). Each category of SD has been observed in persons with concussion (Wickwire et al., 2016). Most commonly, people report experiencing excessive nighttime and daytime sleep, reduced nighttime sleep, daytime drowsiness and fatigue, difficulty initiating or staying asleep, insomnia, and frequent nighttime awakenings (Jaffee et al., 2015; Kostyun, 2015; Morse & Kothare, 2018; Ouellet et al., 2015; Rose et al., 2015). Most evidence of SD following concussion is derived from subjective studies in adult populations, with few studies examining post-concussion SD in youth. Information from the available literature in children and adolescents will be the primary focus of this thesis, however information from adult studies will be used to provide further support to ideas.

Most evidence supports than in all-severity TBI, approximately 30-70% of people will experience some form of SD, with high incidences of insomnia, hypersomnia, and sleep apnea (Mathias & Alvaro, 2012; Fichtenberg et al., 2002; Makley et al., 2008; Ouellet & Morin, 2006). In a recent review, insomnia was estimated to occur in approximately 40-65% of persons with concussion (Zhou & Greenwald, 2018). In a review paper examining the prevalence of SD by TBI severity, Orff et al., 2009 found that there were more reports of SD in those with concussion compared to those with more severe forms of TBI. The researchers suggest that this occurs because these concussed individuals are more likely to return sooner to ‘normal’ daily activity before clinically recovering, therefore exacerbating and prolonging any sleep issues experienced.

The general incidence and duration of SD in concussion-specific youth populations is not well defined. Estimates of SD incidence rates in children and adolescents are informed by only a few studies that specifically assessed post-concussion sleep trends. One estimate comes from a recent study of 517 youth ages 6 to 18 with concussion, finding that that 27.3% of participants were considered poor sleepers after injury when classified using the Pittsburgh Sleep Quality Index (PSQI; Chung et al., 2019). In another study from 2005 to 2011, it was found that 34% of 417 patients ages 13 to 18 reported having subjective issues with their sleep following a concussion (Bramley et al., 2017). Although, it should be noted that the PSQI has not been validated in children, nor has it fully been validated in adult TBI populations. Thus, the generalizability of results between studies are limited.

The clinical course of post-concussion SD issues are not well defined. In some studies in adults, SD has been shown to persist months (Tham et al., 2015) to years after TBI (Grima et al., 2017; Imbach et al., 2016; Orff et al., 2009; Towns et al., 2015). For instance, in a study of 346 adults with concussion by Theadom et al., 2015, 41.4% of participants were found to have clinically significant SD at one year post-injury, with a prevalence of insomnia three times greater than the rate of the general public when assessed using the PSQI. Assessment of sleep quality from 6 to 12 months showed that sleep quality improved in 44.9% of the sample, while 16.2% remained the same, and 38.9% reported that their sleep quality had worsened. These results seem to demonstrate that SD is common after concussion and that while SD may improve in some people, there is a likely chance that these sleep issues persist or develop well after the injury.

1.32 Pathophysiology of Post-Concussion Sleep Disturbance

While still unclear, post-concussion SD is thought to result from impairment in the signaling of neurons in sleep regulation centres in the brain, circadian rhythm systems, and in brain systems involved in pain and anxiety sensitivity (Ayalon et al., 2007; Grima et al., 2017;

Morse & Kothare, 2018; Viola-Saltzman & Watson, 2012). Researchers have shown that melatonin, an important regulator of sleep and circadian rhythm, and orexin, a neuropeptide involved in arousal and wakefulness, is reduced in the evening in persons with TBI when compared to controls, likely resulting in impaired regulation of normal sleep-wake patterns (Baumann et al., 2005; Grima et al., 2016; Shekleton et al., 2010). Although, some evidence in adult TBI populations have found that melatonin rhythms do not seem to be significantly different from non-TBI trauma patients (Duclos et al., 2017). Furthermore, most of this research pertains to moderate and severe cases of TBI and is not necessarily generalizable to concussion. It is also hypothesized that this dysregulation of signaling and neurotransmitter release is also implicated in the manifestation of coincident psychiatric symptoms and other co-morbidities (Jaffee et al., 2015). However, given the wide range and variability of clinical sleep symptoms endorsed by persons with TBI, it is likely that there is are several brain systems affected and it is unlikely that all persons with post-concussion SD experience the same form of pathophysiology (Viola-Saltzman & Watson, 2012). It is also likely that clinical features such as pain, often resulting from headaches, as well as anxiety and maladaptive behaviours that result due to concussion also influence sleep behaviour and the likelihood of developing SD (Lavigne et al., 2015; Rao et al., 2008; Suzuki et al., 2017; Wickwire et al., 2016). More research into the underlying neural mechanisms and pathology is needed to properly understand how concussion contributes to SD.

1.33 Changes in Sleep Following Concussion

By comparing sleep characteristics of concussed individuals to control groups, researchers have begun to understand how the subjective and objective aspects of post-concussion sleep differ from normal populations. However, few studies have made these comparisons, especially in youth populations. Of the few studies available, one prospective cohort compared the sleep 5 to 12 months post-injury of 50 adolescents with prolonged concussion recovery to 50 healthy adolescents using the Adolescent Sleep Wake Scale (Tham et al., 2015). Researchers found that the concussion group reported poorer subjective sleep quality, greater difficulty reinitiating sleep, falling asleep and returning to wakefulness, as well as greater levels of pre-sleep arousal when compared to the healthy control group. When sleep was objectively measured using actigraphy, the researcher found that the concussion group had significantly shorter TST (5.90 hours vs. 6.52 hours), poorer SE (74.6% vs. 81.1%), and a greater WASO (112 minutes vs 79 minutes) when compared to healthy controls. Similarly, in a recent study by Hoffman et al., 2019, researchers compared the outcomes from three subjective sleep questionnaires and actigraphy measures in 20 concussed to 20 non-concussed college students throughout stages of recovery. When assessed subjectively, it was identified that the concussed participants reported poorer overall sleep quality when compared with non-concussed participants. When assessed through actigraphy, the researchers only found that persons with concussion took significantly longer to initiate sleep 2 to 3 days post-injury and had greater intraindividual variability in sleep fragmentation and sleep duration throughout recovery. Evidence from these studies seems to demonstrate that persons with concussion show evidence for subjective and some objective changes in their sleep when compared to healthy individuals, particularly in measures of sleep quality, sleep duration, sleep onset latency, and daytime napping.

However, it is important to note that research does not always support that sleep is significantly altered following concussion. In a recent longitudinal study comparing sleep outcomes in children and youth using the Bruni Sleep Disturbance Score, there were no significant within- or between- group differences in sleep over 12 months between those with concussion and healthy or orthopedically injured age- and sex-matched participants (Wiseman-Hakes et al., 2019). When groups were divided by age, children ages 6 to 11 with concussion did show significant differences in their ability initiate sleep and had greater daytime nap duration, but only when compared to healthy controls and not those with orthopedic injury. Furthermore, observable changes in sleep may be dependent on the method of sleep measurement. In a small study of 10 concussed young adult athletes using both subjective and objective measures of sleep, Gosselin et al., 2009 found that when compared to 11 healthy controls, adult athletes reported significantly worse sleep quality, sleep disturbances, and daytime dysfunction on a subjective sleep questionnaires, but did not show any objective differences in any sleep variables when comparing PSG outcomes. Similarly, another study in adults found that participants reported significant subjective changes in sleep, yet when compared through actigraphy, the only significant change in sleep was that people attempted to sleep at a later time (Allan et al., 2017). Moreover, a meta-analytic study examining changes in sleep after TBI, found that the sleep architecture of persons with concussion may not be significantly different than healthy persons (Mantua et al., 2018).

Evidence from these studies highlight important discrepancies between what participants report subjectively and what is observed objectively. A study by Berger et al., 2017 explored this type of discrepancy in a small group of children with concussion, finding that actigraph measures of sleep quality did not correlate well with participants PSQI scores. This suggests that while both measures are important to consider, they may be assessing different aspects one's sleep. This difference may be explained as a result of an overestimation of SD. For instance, persons with TBI have been shown to overestimate their insomnia symptoms when compared with their respective PSG recordings (Ouellet & Morin, 2006). Perhaps changes in post-concussion sleep quality are mostly subjective in nature and are not as significantly different from healthy persons when measured objectively. This may explain why researchers observe such significant variability in results when comparing objective and subjective sleep outcomes. Alternatively, it may be that subjective complaints are corroborated but objective measures are unable to detect what causes the subjective complaint. This thesis will explore this phenomenon in further detail.

1.34 The Effects of Post-Concussion Sleep: Post-Concussion Outcomes

Unsurprisingly, these changes in a person's sleep can have a multitude of consequences and can affect post-concussion outcomes. The consequences of SD in youth have been briefly explored in a large cohort study of children by Chung et al., 2019. In the study, 517 youth under the age of 18 with concussion were divided into good sleepers and poor sleep based on their PSQI score and were then compared. At initial assessment and at 3-months post-injury, those categorized as poor sleepers were found to have significantly greater symptom scores, anxiety ratings, and depression scores when compared to the good sleepers. Similarly, in a large study of adults with concussion by Theadom et al., 2015, poor baseline sleep, as determined by the PSQI, was determined to be significantly predictive of poorer post-concussion symptoms, cognitive ability, mood, depression, anxiety, and social integration. Interestingly, after controlling for other participant variables, the only significant predictor of post-concussive symptoms was the severity of one's sleep-related symptoms. Perhaps the reciprocal interaction between SD and symptoms exacerbation explains this finding.

Several other studies in concussion-specific populations have shown a relationship between poor post-concussion sleep and exacerbation physical, psychiatric, and neurocognitive post-concussion symptoms (Blake et al., 2019; Hinds et al., 2016; Hoffman et al., 2017; Kostyun et al., 2015; Towns et al., 2015; Lavigne et al., 2015), as well as significant correlations with quality of life (QOL) dysfunction (Blake et al., 2019). Furthermore, research by Sufrinko et al., 2015 has also shown that persons with pre-injury sleep difficulties, defined as sleeping less as well as having trouble falling asleep, reported significantly more concussion symptoms and performed significantly worse on several neurocognitive tests up to 14 days after injury. Collectively, these studies provide evidence that supports an important association between sleep and post-concussion outcomes, providing further reason to explore post-concussion sleep and its implications in recovery from concussion.

1.35 The Effects of Post-Concussion Sleep: Recovery

While SD is mainly considered one of many post-concussion symptoms, some research suggests that sleep may also be causally associated with recovery length. Many of the symptoms associated with SD, such as fatigue, daytime sleepiness, depression, elevated pain sensitivity, and concentration issues, are commonly displayed in those with PPCS (Orff et al., 2009). While evidence is sparse, results from some studies in adults and children appear to indicate a close relationship between sleep and concussion outcomes. A cross-sectional study performed on 158 adults with a history of concussion found that 88% of participants with PPCS were also found to have poor sleep, as measured by the PSQI (Towns et al., 2015). Similar results were found by Hinds et al., 2016, who observed that mild-to-severe SD was exhibited in 57% of the population with PPCS when measured by the Insomnia Severity Index. When using predictive regression modeling, after controlling for age, gender, and days since injury, researchers found that the only significant predictor of PPCS was the severity of one’s sleep-related symptoms. These associations have led researcher to believe that post-concussion sleep quality is actively associated with the length and likelihood of recovery (Bramley et al., 2017; Chung et al., 2019; Hinds et al., 2016; Hoffman et al., 2017, 2019).

Research into this relationship is relatively new, however a few studies have shown that poor sleep quality is related to longer recovery times in children and adolescents. In the study by Chung et al., 2019, when comparing good sleepers to poor sleepers, it was found that the poor sleepers took significantly longer to reach symptom resolution and took over two weeks longer to be cleared by a clinician to return to play (35 days vs 20 days, respectively). Of the participants who reached symptom resolution in ≤30 days, 86.4% of them were categorized as good sleepers and only 13.6% were in the poor sleep group. These results provide some evidence to suggest that those with better sleep quality are more likely to recover within the expected time frame. Other research from Hoffman et al., 2019 also found a significant correlations between participants PSQI score and the length of their recovery in college students. A similar association was found in a retrospective chart review of 417 concussed patients ages 13 to 18 who visited a single concussion clinic in Pennsylvania (Bramley et al., 2017). Patients subjectively disclosed if they had experienced any SD and the length of recovery was defined by the time from injury to the last clinic visit where the clinician did not recommend a follow-up visit. Those that self-reported experiencing post-concussion SD recovered in a median of 111 days compared to 29 days in those who did not, demonstrating that that self-identified SD was associated with a 3- to 4- fold increase in recovery time. Although, it should be noted that this study only asked patients two subjective questions regarding their sleep and did not assess SD severity in patients.

While these studies provide important evidence, these results were only demonstrated through subjective measures of sleep quality. Evidence linking objective sleep quality to recovery is significantly lacking. Given that subjective and objective measures of sleep appear to poorly correlate in a concussed youth population (Berger et al., 2017) it is important to determine if this association between recovery and sleep is also observed when using objective measures of sleep quality. To my knowledge, only one study has evaluated this relationship objectively in any concussed population. Hoffman et al., 2019 used actigraphy to measure sleep quality variables throughout the recovery of 16 college students, correlating the number of days it took to reach symptom recovery with the participants actigraphy sleep outcomes at 2-3 days post-injury, as well as the mid-point and end of their recovery. At the mid-point of recovery, researchers identified a moderate positive relationship between wake after sleep onset and days to asymptomatic and a negative relationship between sleep efficiency and days to asymptomatic. Towards the end of recovery, a moderate positive relationship between total sleep time and days to asymptotic was also identified. This study provides preliminary evidence that some elements of objective sleep quality, particularly in the mid- to later stages of recovery, are associated with length of time to reach symptom resolution. However, this study only contained a small sample size and did not control for any individual participant variables such as age, sex, initial symptoms score, and previous concussion history. Nor does correlation analysis permit an understanding of the directionality of a given relationship. Given the lack of controlling factors and small sample size, the strength of these results are limited and the directionality between recovery and sleep quality cannot be assumed. More research is needed to understand the extent to which sleep quality is related to recovery.

1.36 Restorative Theory of Sleep and Recovery from Concussion

The Restorative Theory of Sleep

Perhaps the most reasonable explanation that describes the role of sleep in concussion recovery can be derived using the restorative theory of sleep. The restorative theory of sleep postulates that sleep functions as a period of low activity to restore depleted sources of energy, remove waste, and repair cells so that adequate cognitive and biological function is regained (Adam, 1980; Mignot, 2008; Oswald, 1980; Vyazovskiy & Delogu, 2014). This theory emphasizes the role of 'restorative sleep' stages and their relation to maintaining normal homeostatic function.

Specifically, the theory places importance on roles of sleep architecture and sleep cycles. Sleep cycles are comprised of three stages of non-rapid eye movement sleep and rapid eye movement sleep (REM). Stages 1 and 2 are considered light stages of sleep and are followed by stage 3 deep sleep, consisting of slow-wave electrical activity. REM sleep occurs subsequent to stage 3 and has similar electrical activity to wakefulness and is when most dreaming occurs (El Shakankiry, 2011). Throughout the day, the body and brain endure biological pressures experienced from wakefulness, exertion, illness, and injury that impair our ability to function optimally. The theory of restorative sleep hypothesizes that the later stages of sleep, specifically stage 3 and REM sleep, provide complementary molecular, cellular, and network level restoration that is implicated in, and needed for, biological recovery from these pressures (Diaz-Aband et al., 2015; Vyazovskiy & Delogu, 2014; Wickwire et al., 2016). Theoretically, this restorative sleep is meant to facilitate processes in synaptic plasticity, subcellular and cellular repair, regulation of neuronal excitability, and other prophylactic cellular maintenance in order to maintain normal healthy function (Adam, 1980; Mignot, 2008; Oswald, 1980; Vyazovskiy & Delogu, 2014).

In general, it is believed that stage 3 sleep is needed to wake up feeling refreshed and renewed and evidence supports that stage 3 sleep is vital for healthy physiological function (Åkerstedt et al., 1997; della Monica et al., 2018). This likely occurs because stage 3 sleep is associated with an increase in protein and hormone synthesis needed for repair functions, (Mackiewicz et al., 2007), and clearance of neurotoxic waste that has been accumulated during wakefulness (Underwood, 2013; Xie et al., 2013). These processes aid in cellular and network level repair to restore biological functions that have deteriorated throughout the day or after insult. For instance, evidence from a meta-analysis of studies examining sleep architecture after chronic TBI found that patients had increased stage 3 slow wave sleep after moderate-severe TBI (Mantua et al., 2018). This is thought to reflect the body's natural compensatory mechanism to increase cortical reorganization and restructuring. Furthermore, in persons with diffuse axonal injury due to traumatic brain injury, increases in sleep-wave activity associated with stage 3 sleep were coincident with improvements in cognitive function (Urakami, 2012). This suggests that increases in stage 3 sleep is reflective of recovery in cognitive function.

Evidence in support of the benefits of REM sleep mainly concern memory consolidation (Rasch & Born, 2013). Evidence in rats show that changes in the concentration of neurotransmitters during REM sleep are associated with the synthesis of proteins necessary for memory integration in the hippocampus (Graves et al., 2001). Less clear however, is how REM sleep directly promotes recovery of neural health (Siegel, 2011). Most support to the idea comes from studies that examine changes in REM sleep architecture as we age. During infancy there is a tremendous neural development that rapidly occurs. Coincidentally, infants spend significantly more time sleeping, with a larger proportion of their sleep spent in the REM stage than adults. As we age through childhood and adolescence, brain development slows, and both the amount of sleep and time spent in REM sleep decrease simultaneously throughout childhood into adolescence (El Shakankiry, 2011). Impairments in REM sleep throughout childhood are associated with increased risk for psychiatric conditions and neurodegenerative disease later in life (Brand & Kirov, 2011). This relationship leads researchers to infer that REM sleep is essential for the development and generation of neural health**.** As such, REM sleep is thought to have a role in neural recovery. However, the true nature and purpose of REM sleep is still rather unknown (Siegel, 2011).

More support to the theory of restorative sleep comes from studying the effects of sleep deprivation or poor sleep quality. Evidence suggests that lack of sleep can result in forms of neurological malfunction that is reflected in functional impairments (Alhola & Polo-Kantola, 2007; Cirelli, 2006; Durmer & Dinges, 2005). As previously described, insufficient sleep or poor sleep quality have been associated clinically with impairment to cognitive performance and memory (Alhola & Polo-Kantola, 2007; Durmer & Dinges, 2005), mental health and behaviour (Alvaro et al., 2013; Taveras et al., 2017), and several aspects of physical health. Poor sleep, specifically in children and adolescents, appears to be associated with academic difficulty (Dewald et al., 2010; Nevéus et al., 2007; Noland et al., 2009; Ohayon et al., 2000; Perez-Chada et al., 2007) as well as poorer athletic performance (Taylor et al., 2016; Watson, 2017) and increased risk of injury (Gao et al., 2019; Milewski et al., 2014). Evidence from these studies strongly supports the role of sleep in maintaining several aspects of health and one's ability to function normally. This is thought to reflect that sleep is involved in restorative functions that are needed for optimal physical and neuronal health.

Restorative Sleep and Recovery from Concussion

Using the principals of the restorative theory of sleep, the relationship between post-concussion sleep and recovery can be explained. It is well established that TBI and concussion can result in changes in sleep behaviour. TBI and concussion are associated with symptoms causing pain, anxiety, as well as physical and cognitive fatigue that likely result in an increased demand for sleep (Kenzie et al., 2018; Suzuki et al., 2017; Wiseman-Hakes et al., 2016). Theoretically, this drive for sleep is the result of the body's natural compensatory mechanism that attempts to increase the amount of late-stage restorative sleep in order to promote neural recovery (Kenzie et al., 2018; Mantua et al., 2018). However, this process may become impaired in the instance of post-concussion SD, which can contribute to increased arousal and sleep fragmentation (Mathias & Alvaro, 2012; Morse & Kothare, 2018; Ouellet, et al., 2015; Ouellet & Morin, 2006; Parcell et al., 2008; Wickwire et al., 2016). These frequent arousals interrupt the sleep cycle, causing reversion to wakefulness and the cycle must begin anew. Consequently, this will limit the amount of time spent in the later, restorative stages of sleep, therefore disrupting the stages of sleep necessary for biological healing and impairing recovery. Thus, under this model, those who experience less, or do not experience SD at all, will have better sleep quality, therefore achieving more restorative sleep and recovering faster. Conversely, the sleep of persons with post-concussion SD will be frequently interrupted, limited the amount of restorative sleep achieved, resulting in a slower recovery. Similar ideas have been proposed by Kenzie et al., 2018 in an article that described causal relationships between pathophysiological features of concussion and their influence in recovery. An adapted version of the causal-loop diagram depicted by Kenzie et al., 2018 is shown in **Figure 1** to illustrate this theory.

It should be noted that this theory is conditional on the hypothesis that concussion-related SD result in objective changes in sleep and sleep architecture. While evidence for objective sleep changes are somewhat mixed, evidence from a 2018 systematic review and meta-analysis indicates that that sleep architecture may not be significantly altered after concussion (Mantua et al., 2018). This is a significant limitation of the proposed theory of sleep and concussion recovery.

1.37 Predictors of Post-Concussion Sleep Quality

Considering that post-concussion sleep quality appears to be somewhat associated with post-concussion outcomes and recovery, it is important to understand what factors may increase the risk of developing SD after concussion. However, given the current evidence, there are no consistent predictors of post-concussion SD. Studies often provide results that conflict with those of others and nearly all relevant literature exclusively pertains to subjectively measured sleep behaviour.

In the study by Chung et al., 2019, participant factors were compared between the good sleep and poor sleep groups. The poor sleep group was found to be significantly older, contained more females, had a previous diagnosis of psychological disorder, had a history of headache or migraines, and to have had a previous brain injury. The researchers also note that on average, more of the participants in the poor sleep group returned to play immediately following their injury and presented to the clinic later than those in the good sleep group. These results indicate that there may be both unmodifiable and modifiable factors that could contribute to SD following a concussion. However, other studies have shown conflicting results. In the study by Bramley et al., 2017, no differences in age, sex, or past number of concussions were found when comparing those who reported SD to those who did not. The only significant predictor of SD was the mechanism of injury, finding that non-sport related concussion was more likely to result in SD than sport-related concussions. Similarly, other studies have shown that age, sex, and number of concussions were not significantly associated with SD (Hinds et al., 2016; Theadom et al., 2015). But these findings contradict those from other studies, including a 2009 systematic review that found that those with sports related concussion were more likely to report SD and that a history of concussion could influence the severity of SD symptoms (Orff et al., 2009). Results from other studies provide further confusion, with some finding that younger ages (6 to 11)

(Wiseman-Hakes et al., 2019) and being male (Towns et al., 2015) are associated with post-concussion SD. Anxiety, depression and pain have also been found to increase a persons risk of post-concussion SD (Ponsford et al., 2013). Studies using PSG to measure sleep have also found no sex differences in the distribution of sleep stages in a population of adults with concussion (Mollayeva et al., 2017).

Ultimately, it appears unclear what individual factors consistently predict SD in a concussion population. Perhaps, there may be an influence from certain individual characteristics that were not measured but are known to cause SD in healthy individuals, such as stress, parental factors, and academic performance (Ishak et al., 2017; Kesintha et al., 2018). Alternatively, this may suggest that each person possesses their own unique susceptibility to post-concussion SD. However, without more data or large reviews it is difficult to identify what factors are associated with a person's risk of developing post-concussion SD.

1.4 Post-Concussion Health Outcomes

1.4 Post-Concussion Depression

In addition to prolonged symptoms, many people have become concerned with depression as an outcome following concussion. Depression is a complex mood disorder that can cause persistent feelings of sadness, loss of interest, hopelessness, and disordered sleep. It is associated with substantial morbidity and mortality and can be reflected in adverse outcomes in a persons physical and mental health, academics, employment, substance use, and QOL (Fergusson & Woodward, 2002; Glied & Pine, 2002; Richardson et al., 2003). In children and adolescents, there is reasonable evidence to suggest that concussion is associated with an increased risk of depression-like symptoms and a higher likelihood of being diagnosed with depression (Chrisman & Richardson, 2014; Emery et al., 2016; Kirkwood et al., 2001; Manley et al., 2017). In a large retrospective study, adolescents with a history of concussion were found to have a 3.2 fold greater risk for depression diagnosis than adolescents without (Chrisman & Richardson, 2014).

Depression most often occurs subsequently to significant chronic or sudden life stressors (DeJean et al., 2013; Hankin, 2006). However, everyone's susceptibility to depression is dependent on a number of environmental, genetic, and neurobiological factors (Caspi & Moffitt, 2006; Hankin, 2006). In people with inherent susceptibility, it is possible that concussion acts as the significant stressor that can trigger depression-like symptoms and clinical depression itself (Yrondi et al., 2017). In fact, many of the symptoms elevated following concussion, such as emotional irritability and sadness, behaviour changes, fatigue, concentration and memory issues, as well as sleep disturbances are congruent with symptoms also expressed in persons with depression (Emery et al., 2016; Kontos et al., 2012). This may be suggestive of a bi-directional relationship between concussion and depression. However, it is often hard to distinguish between concussion-related symptoms of depression or an underlying mental health issue, considering that there is still limited evidence to suggest that these psychological issues persist beyond the acute phase of concussion (Emery et al., 2016).

Sleep and Depression

Literature regarding depression and anxiety in a non-concussed population finds that sleep behaviour and quality strongly influences multiple aspects of a person's depression or psychiatric illnesses (Alvaro et al., 2013; Kouros & El-Sheikh, 2015; Nutt et al., 2008; Van Dyk et al., 2016). Results from a meta-analysis of 21 studies found that persons with insomnia were two times more likely to develop depression (Baglioni et al., 2011). In a study examining adolescents presenting with insomnia, the rate of mental health diagnoses was significantly greater than the normal population and participants reported significantly elevated clinical symptoms of mental illness (Van Dyk et al., 2019). Researchers suggest that this is reflective of a bidirectional relationship between sleep issues and psychiatric disorder (Alvaro et al., 2013; Krystal, 2012). This is not particularly surprising considering that those with anxiety and depression frequently endorse complaints of disordered sleep (Nutt et al., 2008). Conversely, youth who report worse sleep quality are more likely to report greater symptoms of anxiety and depression (Roeser et al., 2012; Sarıarslan et al., 2015; Willis & Gregory, 2015).

This relationship has been briefly explored in a few TBI populations. In the study by Chung et al., 2019, children who were deemed poor sleepers reported significantly more symptoms of depression and anxiety than the good sleepers group when compared on the Patient Health Questionnaire and the Generalized Anxiety Disorder Scale, respectively. Theadom et al., 2015 also found that poor sleep was significantly associated with worse scores on measures of depression and anxiety in a group of adults with concussion when measured with the Hospital Anxiety and Depression Scale. Similarly, other studies investigating all severity TBI in adults have observed a strong relationship between sleep difficulties and a higher comorbid diagnosis of depression, anxiety, and pain, up to, and beyond 1-year post-injury (Fogelberg et al., 2012; Kempf et al., 2010; Parcell et al., 2008; Shekleton et al., 2010). evidence from these studies demonstrates that subjective indication of poor sleep is likely predictive of depression and anxiety.

Only one known study has reported on this relationship using objective sleep measures. In a sample of 12 adults with persistent symptoms from mild-severe TBI, researchers found that individualized treatment for sleep/wake disorders resulted in positive improvements in PSG measures which corresponded with decreased depression symptomatology (Wiseman-Hakes et al., 2013). This suggests that objective sleep changes may influence depression symptomatology after brain trauma.

While these studies appear to indicate some apparent link between concussion, depression, and sleep, it cannot validly comment on the direction of association between them. Nor can these studies conclusively demonstrate the post-concussion SD is a predictor for developing clinical depression. Regardless, it is important to continue to study this relationship between post-concussion sleep quality and depression and anxiety to hopefully better understand how concussion contributes to their development. Future research attempts should be directed at establishing if similar relationships are observed when measuring sleep objectively.

1.42 Quality of Life After Concussion

Quality of life (QOL) describes the overall wellbeing of a person by assessing several physical, mental, and social domains of their health. There is concern that the symptoms and recovery processes following concussion can lead to deficits in these domains, thereby negatively effecting the QOL children and adolescents (Fineblit et al., 2016). If a child experiences physical, behavioural, and cognitive burden post-concussion, it may impair their overall wellbeing resulting from, and contributing to, decreased participation and difficulty in social activities, academic problems, isolation, and difficulty in regular daily functioning (DeMatteo et al., 2014; Marsh et al., 2013; McCrory et al., 2017; McLeod et al., 2017; Russell et al., 2019; Todd et al., 2018).

These elements of a children's QOL are important to consider, however few studies have looked at post-concussion QOL in children and adolescents. The available literature provides some evidence that youth experience some decreases in variable domains of their QOL (DeMatteo et al., 2014; Moran et al., 2012; Russell et al., 2019). Although, there is a lack of consistency in describing how long these issues persist. One study comparing 135 adolescents with sports related concussion to 96 adolescents with sports related orthopedic injury, found that those with concussion had clinically meaningful decreases and significantly worse QOL when measured by the Pediatric Quality of Life Inventory (Russell et al., 2019). Participants reported significantly worse cognitive, school, and overall QOL during the acute assessment than persons with orthopedic injury, but all impairments to QOL were resolved at the time of clinical recovery. In contrast, DeMatteo et al., 2014 found that when assessed with the Child Health Questionnaire, all domains of QOL were significantly worse in children with concussion when compared to a normative sample. Other than at baseline, these differences were seen up to 5 years post-injury, particularly in participants psychosocial scores. Similarly, Moran et al., 2012 and Novak et al., 2016 also found that children with concussion report long-term deficits in their QOL. When compared with an orthopedic injury group, the concussion cohort were observed to have lower QOL up to 1 year-post injury. However, unlike DeMatteo et al., 2014, significant differences were only observed in the physical QOL domain and not in psychosocial outcomes. The researchers also highlight that there was significant variance in the QOL when measured at 3 months and significant variance in the rate of change in QOL from 3 to 12 months. This may suggest that some people may be more vulnerable to experience clinical deficits in QOL that others.

Given the sparsity of the literature, it is difficult to draw many conclusions about a person's susceptibility to declines in their QOL. From studies available, it appears that the children who report declines in QOL tend to endorse more acute and post-acute symptoms that persist beyond the expected recovery period (Houston et al., 2016; Howell et al., 2019; Moran et al., 2012; Russell et al., 2019). Rather intuitively, the information from these studies seems to suggest that people who experience a greater degree or duration of concussion-related symptoms burden will be more likely to have issues in their QOL outcomes post-concussion.

Sleep and Quality of Life

It is also likely that sleep plays an important role in QOL outcomes in youth post-concussion. As previously discussed, sleep is vital in the maintenance of cognitive, mental, physical, and social health, which are all encompassed in a person's overall QOL. There are several examples of studies that support the association between sleep and QOL in healthy populations of children and adolescents, where poor subjective sleep quality is related to worse QOL (Roeser et al., 2012; Sarıarslan et al., 2015; Xiao et al., 2019). This relationship was also shown in a large-scale study of 3974 children, where researchers found that people who had either disordered sleep or minor sleep disturbance endorsed worse QOL scores on all domains of the PedsQQL measure of QOL (Magee et al., 2017). In addition, when associated with poor sleep, QOL was observed to worsen over time. Only one study was found that described the relationship between post-concussion sleep and QOL outcomes. In a sample of 82 athletes ages 18 to 25, Blake et al., 2019 observed that the number of self-reported sleep disturbances were moderately, but significantly, correlated with the number of QOL dysfunctions and the severity of QOL impairment. These studies appear to support a relationship between sleep quality and QOL outcomes in healthy and adult concussed populations. Given this, and given that post-concussion SD appears to influence symptom exacerbation, PPCS, recovery, and mental health, it is likely that there is also a relationship between post-concussion sleep quality and QOL outcomes in children and adolescents.

1.5 Research Purpose

The issue of SD following concussion is not a new concept, and it is well known that healthy sleep is integral to our overall health. Yet, despite the prevalence and the concern, sleep is not often assessed in concussion management or in rehabilitation strategies (Grima et al., 2017; Mosti et al., 2016; Orff et al., 2009). Likely, this has occurred because this area of concussion research is understudied and information regarding sleep and concussion is sparse, resulting in limited literature to guide clinical practice. Sleep may be an important missing piece in concussion management, since abnormalities in sleep components appear to negatively impact recovery and post-concussion outcomes. However, we do not sufficiently understand 1) if there are changes in objective sleep quality following concussion; and 2) if objective post-concussion sleep quality is implicated in recovery and health outcomes. Our current knowledge is limited by the fact that there are:

- few studies that have examine objective measures of sleep quality post-concussion. Even fewer have been done in youth populations;
- inconsistencies in the literature about post-concussion sleep changes and predictors of post-concussion sleep quality;
- no studies that have longitudinally described how sleep quality changes from injury and throughout the course of recovery;
- few studies that have examined how post-concussion sleep quality influences recovery and only one small study has examined the association between objective sleep quality outcomes and recovery timeline;
- and, no known studies have examined the association between objective post-concussion sleep quality and depression and QOL outcomes.

The purpose of this thesis is to address these gaps in knowledge in order to advance our understanding of post-concussion sleep behaviour and its influences in children and adolescents. Actigraphy data from a prospective cohort of 79 children and adolescents with concussion progressing through RTS and RTA protocols were used to assess sleep quality over the first 4 weeks of recovery. Measures of total sleep time, sleep efficiency, wake after sleep onset, average number of arousals, and average arousal length were used to assess sleep quality. Using this data, Chapter Two will address the following questions and objectives:

1) Do objective sleep parameters in children and adolescents with concussion differ from normal sleep estimates derived from healthy youth?;
2) Describe the longitudinal trends of objective sleep parameters throughout the first 4 weeks of concussion recovery; and
3) Determine if demographic, pre-injury, injury-related, or time-related factors are associated with objective sleep parameters throughout recovery.

In Chapter Three, I will address if weekly sleep parameters within the initial 4 weeks of recovery are:

1) Associated with the number of days to return to school and return to activity in children and adolescence with concussion;
2) Correlated with QOL and depression symptomatology outcomes at 3-months post-recovery or 6-months post-injury, as measured by The Kidscreen Questionnaire (52-item) (Ravens-Sieberer et al., 2005) and the Children's Depression Inventory (Version 2) (Kovacs 2011), respectively; and
3) Correlated with changes in QOL and depression symptomatology outcomes.

Answering these questions will provide valuable and novel information that can be used to clarify how concussion affects sleep and, if sleep is implicated in the recovery and health outcomes of children. The results of these studies are integrated and discussed in Chapter 4 along with the clinical implications associated with this research. In conjunction with previous and future literature, this research will help to more formally evaluate whether sleep quality should be more actively addressed following concussion. It will also help address whether future research efforts should be directed towards sleep therapy and its utility and efficacy in promoting recovery from concussion.

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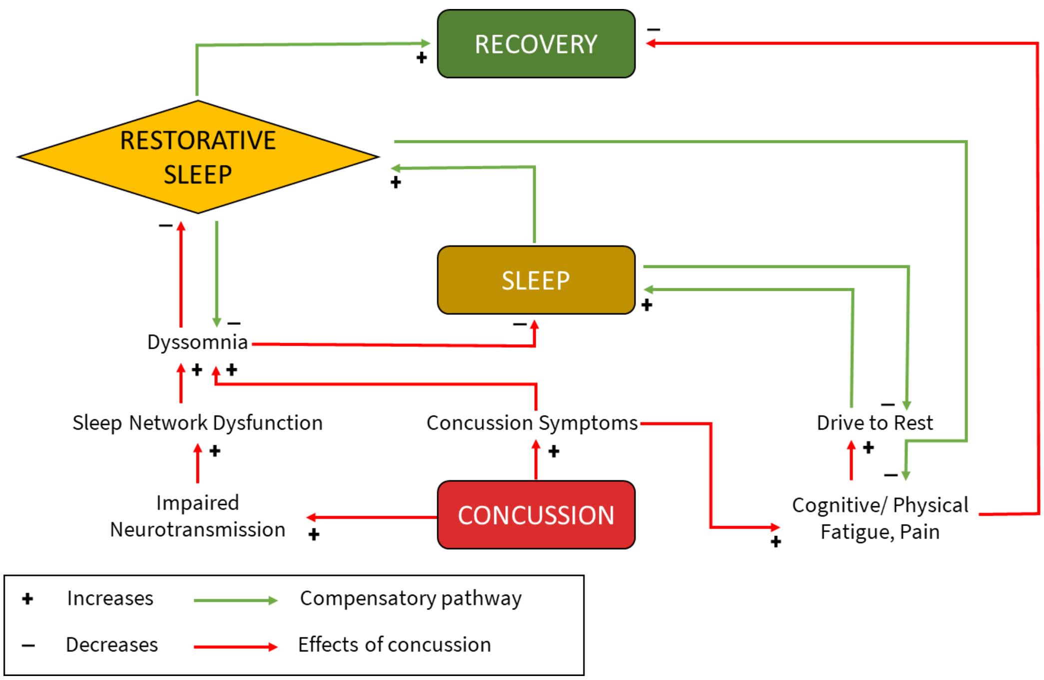

Figure 1. Causal-loop diagram of concussion, sleep, and recovery (adapted from Kenzie et al., 2018). The diagram illustrates the proposed causal flow of concussion to recovery in relation to restorative sleep function of sleep theory. The adverse effects of concussion are illustrated with red arrows, demonstrating how concussion may impair the ability to achieve restorative sleep and recovery. The hypothesized compensatory mechanism to promote restorative sleep and recovery is illustrated with green arrows.

Table 1. Estimates of total sleep time by age group across different studies.

Study	Methods of Measurement	Sample Size (n)	Total Sleep Time (hours)	
CDC Guidelines#		N/A	3-5 years old:	11-13
		N/A	5-10 years old:	10-11
		N/A	10-18 years old:	8.5-9.5
Williams et al., 2013	Subjective: Sleep time-diary entry	1083	birth-4 years old:	11.8*
		1478	5-8 years old:	10.3*
		2088	9-12 years old:	9.8 *
		1583	13-16 years old:	9.0*
		541	17-19 years old:	8.8*
Maslowsky and Ozer, 2013	Subjective: Self-reported	1129	13 years old:	8.5
		2870	14 years old:	8.3
		3888	15 years old:	8.0
		4858	16 years old:	7.7
		5288	17 years old:	7.5
		5101	18 years old:	7.3
Galland et al., 2018	Objective: Actigraphy	557	3-5 years old:	9.68
		1598	6-8 years old:	8.98
		1367	9-11 years old:	8.85
		870	12-14 years old:	8.05
		703	15-18 years old:	7.40

= CDC values are recommended values not derived from primary data.
* = median values estimated from study figures.

Table 2. Description of common measures used to assess sleep after concussion.

Sleep Measure	Description of Measure	Type of Measurement	Advantages	Disadvantages
Actigraphy	Small, portable device worn on the wrist, ankle, or waist during sleep. Using an algorithm, raw data is converted into estimates of sleep-wake behaviour.	Objective. Measures acceleration to detect gross movement.	Feasible for repeated nightly use. Eliminates laboratory effects. Continuous measurement of sleep. Measures multiple characteristics of sleep behaviour.	More expensive. Poorly detects wakefulness (low specificity). Scoring and interpretation is time-consuming.
Polysomnography (PSG)	Considered the gold-standard of sleep-wake quantification. Electrodes are placed on participants during sleep. Using an algorithm, raw data is converted into estimates of sleep-wake behaviour.	Objective. Records brain waves, eye movement, muscle movement, and heart rhythm.	Most accurate detection of sleep-wake and sleep cycle patterns. Can be used to distinguish between different sleep disorders. Measures multiple characteristics of sleep behaviour.	Expensive. Time consuming. Not feasible for repeated nightly measurements. Laboratory effects may influence sleep behaviour.
Pittsburgh Sleep Quality Index (PSQI) (Buysse, et al., 1989)	19-item questionnaire assessing 7 components of sleep quality (sleep duration, disturbance, latency, efficiency, daytime dysfunction, sleep quality, medication use).	Subjective. Self-reported answers on a 0-3 interval scale. A global score >5 indicates disturbed sleep.	Accessible. Easy scoring and results interpretation of sleep quality and insomnia. Widely used in research.	Sensitive to participant exaggeration. Less sensitive to symptoms of hypersomnia and circadian rhythm shift.
Epworth Sleepiness Scale (Johns, 1991)	Rates participants tendency to become sleepy in 8 situations to assess daytime sleepiness.	Subjective. Self-reported answers on a 0-3 interval scale of likeliness to fall asleep.	Accessible. Easy scoring. Provides information on the severity of daytime sleepiness and dysfunction.	Sensitive to participant exaggeration. Uses hypothetical situation-based questions to approximate sleepiness.
Insomnia Severity Index (Bastien, Vallières, & Morin, 2001)	7-item questionnaire assessing symptoms and severity of nighttime and daytime insomnia.	Subjective. Self-reported answers on a 0-5 interval scale about perceived sleep behaviour.	Accessible. Easy scoring and results interpretation about the severity of insomnia being experienced	Sensitive to participant exaggeration. Only addresses symptoms of insomnia and not other forms of sleep disturbance that may be present.
Post-Concussion Symptoms Scale (PCSS) (Lovell & Collins, 1998)	21-item questionnaire assessing general concussion symptom severity. 3 questions regarding changes in sleep timing habits (trouble falling asleep, sleeping more than usual, sleeping less than usual).	Subjective. Self-reported answers on a 0-6 interval scale of symptom severity.	Accessible. Easy scoring. Quick assessment for the absence or presence of sleep disturbance.	Sensitive to participant exaggeration. Uses only a few questions to address sleep. Questions about sleep disturbance are relatively non-specific. Does not provide a comprehensive understanding of sleep behaviour or disturbance.
Sleep Diaries	A logbook where participants indicate the time they went to bed, time they fell asleep, time they work up, and number/ length of awakenings.	Objective. Self-reported indication of sleep timing information the following morning.	Accessible. Easy to complete. Often used to support information from other sleep measures.	Sensitive to participant memory error.
Sleep and Concussion Questionnaire (Wiseman-Hakes, et al., 2017)	A 12-item questionnaire evaluating changes in sleep in response to concussion over time.	Subjective. Self-reported indication of sleep issues and changes in sleep over time.	Monitors sleep changes compared to pre-injury baseline sleep and over time. Quick assessment. Validated in children ages 12-18 and preliminary validation with PSG.	Sensitive to participant exaggeration.

CHAPTER TWO:

TRAJECTORY AND PREDICTORS OF SLEEP QUALITY IN CHILDREN AND ADOLESCENTS POST-CONCUSSION.

2.1 Abstract

Introduction: Subjective reports of sleep disturbance are common amongst youth with concussion. However, there is limited research describing how the objective sleep parameters of sleep that inform sleep quality of youth are affected following concussion.

Objectives: This study aimed to: 1) determine if post-concussion sleep quality of children and adolescents differs from normal estimates of sleep quality; 2) describe longitudinal changes in sleep quality throughout the initial 4 weeks of recovery; and 3) determine what factors are associated with sleep quality outcomes.

Methods: Actigraphy was used to measure sleep of 79 children and adolescents up to 4 weeks post-concussion. Sleep quality was evaluated through five sleep parameters: total sleep time (TST), sleep efficiency (SE), wake after sleep onset (WASO), number of arousals per hour (NOA), and average arousal length (AAL). Weekly sleep outcomes were compared with actigraphy sleep data of healthy children and adolescents using single sample t-tests. Predictors of sleep outcomes were assessed using multivariate mixed effects models.

Results: When compared to normal sleep data, adolescents with concussion had significantly longer TST and both child and adolescent participants experienced significantly poorer SE and longer WASO duration throughout 4 weeks of recovery. Some trends of improvement over time were observed for measures of TST, SE, WASO, and AAL in child participants and in measures of SE and WASO in adolescent participants. Older age was associated with longer TST ($p = 0.003$), days since injury was associated with SE improvements ($p = 0.047$), and female sex was associated with longer WASO ($p = 0.025$) and AAL duration ($p = 0.044$).

Conclusions: The parameters of sleep that reflect sleep quality in youth are affected following concussion, particularly in females. Sleep parameters appear to recover with time, especially for children. However, sleep quality parameters may require more than 4 weeks to return to normal for both males and females.

2.2 Introduction

Post-concussion sleep disturbances (SD) are commonly reported in children and adolescents. Recent studies show that approximately 27-34% of children and adolescence self-report experiencing some form of SD following concussion when measured with the Pittsburgh Sleep Quality Index (Bramley et al., 2017; Chung et al., 2019), a common assessment tool used to evaluate subjective sleep quality. A person with SD may experience subsequent alterations in their sleep patterns, circadian rhythm and sleep timing, and may have increased or reduced sleep needs, interrupted sleep, and may develop a clinical sleep disorder (Wickwire et al., 2016b). These disruptions in sleep activity can affect regular sleep cycle behaviour and ultimately impair a persons overall sleep quality (Kaufman et al., 2001; Tham et al., 2015).

Sleep quality is integral to our cognitive, psychological, and physical health (Carrier, 2014; Chaput et al., 2016). Consequentially, impairments in sleep quantity and quality in healthy populations has been associated with poorer cognitive performance, attention, working memory (Alhola & Polo-Kantola, 2007; Durmer & Dinges, 2005), mental health issues (Kouros & El-Sheikh, 2015a; Krystal, 2012), impaired physical performance (Taylor et al., 2016; Watson, 2017) and increased risk of injury during activity (Gao et al., 2019; Milewski et al., 2014). A recent prospective cohort study examining the effects of these post-concussion SD in 517 children and adolescents found that persons deemed ‘poor sleepers’ using the Pittsburgh Sleep Quality Index reported greater exacerbation of post-concussion symptoms, negative mood, depression, and anxiety (Chung et al., 2019). Similarly, a longitudinal study in 346 adults and data from a randomized control study in adults supports that SD is associated with post-concussion cognitive ability, social integration (Theadom et al., 2015), and persistent post-concussion symptoms (Towns et al., 2015), respectively. Other research implicates post-concussion sleep quality in quality of life dysfunction (Blake et al., 2019) and the length of recovery from concussion in children and adolescents (Bramley et al., 2017; Chung et al., 2019). To further appreciate the effects of sleep and its relation to pediatric post-concussion outcomes, it is important to first comprehensively understand how concussion affects sleep quality.

Knowledge regarding pediatric post-concussion sleep quality is sparse and is primarily derived from subjective self-report questionnaires, such as the Pittsburgh Sleep Quality Index. When compared to healthy matched controls, adolescents with concussion report experiencing significantly poorer subjective sleep quality, greater difficulty reinitiating sleep, falling asleep and returning to wakefulness, as well as greater levels of sleep arousal (Tham et al., 2015). However, the clinical course of SD following a concussion is poorly described in the literature. Some studies have found that sleep issues can persist up to months. Furthermore, it is unclear if individual or injury-related factors predict a child’s likelihood of developing post-concussion SD. In a study by Chung et al., 2019, researchers found that the group of children and adolescents deemed subjectively ‘poor sleepers’ contained significantly more females, older participants, and had a greater number of participants with a history of previous concussions, psychological disorder, or migraines when compared to the group deemed ‘good sleepers’. However, another retrospective study found no differences in the distribution of sex, age, or number of concussions between 417 adolescents with and without subjectively reported SD (Bramley et al., 2017).

While these subjective sleep reports are invaluable in assessing how sleep quality is affected by concussion, consideration must also be made towards objective sleep quality measures. Studies that have examined post-concussion sleep quality using both subjective and objective measures have demonstrated that subjective and objective measures of sleep poorly correlate (Berger et al., 2017), often finding that self-reported changes in sleep quality are not always observed when measured objectively (Allan et al., 2017; Gosselin et al., 2009). Consequently, our understanding of how sleep quality is affected as a whole is poorly defined. This is even more apparent in the pediatric literature.

To date, there is little evidence to describe how objective sleep quality is affected after pediatric concussion. One prospective cohort study of 50 children and adolescents with concussion, observed that participants with concussion experienced significantly less sleep duration, poorer sleep efficiency, and increased wake time (Tham et al., 2015). However, participants were recruited 3 to 12 months post-concussion. Consequentially, this study was unable to evaluate the sleep quality of participants specifically within the acute phases of recovery. No known studies have described how objective sleep quality changes longitudinally from injury and throughout the duration of recovery. Nor have any known studies examined predictors of objective post-concussion sleep quality in youth. It is important to clarify these research gaps to more comprehensively understand how sleep quality is affected by concussion in youth. Consideration to these answers may help researchers further address the association between sleep quality and concussion outcomes.

The aim of this study is to use actigraphy to assess the sleep quality trajectory in children and adolescents following concussion and throughout their first 4 weeks of recovery. Actigraphy-derived estimates of participant total sleep time, sleep efficiency, wake after sleep onset, number of arousals per hour, and average arousal length of participants will be used to evaluate objective sleep quality. Specifically, the following research questions and objectives will be addressed: 1) Do objective sleep parameters in children and adolescents with concussion differ from normal sleep estimates derived from healthy youth?; 2) Describe the longitudinal trends of objective sleep parameters throughout the first 4 weeks of concussion recovery; 3) Determine if demographic, pre-injury, injury-related, or time-related factors are associated with objective sleep parameters throughout recovery. We hypothesize that sleep parameters will significantly differ from healthy normal estimates for children and youth but will show trajectories of improvement throughout 4 weeks of recovery.

2.3 Methods

2.31 Study Design

Sleep data was prospectively collected by actigraphy as part of a larger longitudinal cohort study, examining adherence to a return to school (RTS) and return to activity (RTA) protocols in children and adolescents (ages 5-18) with concussion (DeMatteo et al., 2019).

2.32 Ethical Review

The study was approved by the Hamilton Integrated Research Ethics Board at McMaster University. Informed consent was obtained from the parent or legal guardian. Children under the age of 15 provided assent. Youth ages 16 and older provided separate informed consent.

2.33 Participants and Procedures

This prospective study included children and adolescents recruited from the McMaster Children's Hospital Emergency Department and referred from the local community from November 2014 to December 2016. Children and adolescents were included for primary study if they: 1) had a physician confirmed diagnosis of concussion within the past year; 2) were between the ages of 5-18 years; and 3) were still symptomatic at the time of recruitment. Persons were excluded from the study if their injury resulted in admission to a pediatric critical care unit, surgical intervention, and or resuscitation. Participants were included for data analyses if they had available sleep actigraphy sleep data within 28 days of their concussion.

Children and adolescents were instructed by research staff to follow RTS/RTA protocols throughout their recovery. Participant demographic and injury-related information was collected at the time of recruitment. Participants completed an initial assessment of their post-concussion symptoms during recruitment using the Post-Concussion Symptoms Scale (PCSS). Using the PCSS, participants indicated if they had experienced and premorbid conditions, subjective preinjury sleep disturbances, or any sleep disturbances 1 week post-injury. Participants with a symptoms ratings of $\geq$1 on the PCSS 7-point Likert scale were considered to have premorbid or subjective sleep complaints, respectively.

Once informed consent had been given, participants were provided a sleep logbook and an ActiGraph GT3X wrist monitor (ActiGraph^{TM}; ActiGraph, Pensacola, FL, USA) to measure sleep activity and estimate sleep quality parameters. Participants were instructed to wear the ActiGraph wrist monitors at night, using the logbook to validate when they went to bed and woke up. Sleep data from each night was assessed and scored, constituting one nighttime observation.

Given evidence of age-dependent differences in sleep outcomes (CDC, 2010; Galland et al., 2018; Maslowsky & Ozer, 2014; Williams et al., 2013), and, that children and adolescents are sub-groups included in pediatric concussion, participants were divided into two age categories: children, representing participants 5-11 years old, and adolescents, representing participants 12-18 years old. The Berlin 5th Consensus Statement on concussion acknowledges that the expected duration for symptoms recovery is approximately 4 weeks for children and adolescents (McCrory et al., 2017). Given this, and the availability of participant sleep data, the sleep quality of participants was assessed over a 4 week period.

2.34 Measurement: Actigraphy and Sleep Quality Variables

The ActiGraph GT3X wrist monitor is a portable device that captures acceleration in three planes of motion (vertical, anteroposterior, and mediolateral). Using actigraphy, children and adolescents can be assessed in their natural sleeping environment for extended periods of time. Actigraphy is generally considered to be a valid and reliable way of objectively estimating sleep-wake behaviour in healthy children and adolescents (Meltzer et al., 2012; Sadeh, 2011) and is useful in the examining of sleep after traumatic injury (Bigué et al., 2020). Research supports that actigraphy has strong sensitivity to detect sleep, however, actigraphy is limited by poor specificity to detect wakefulness, resulting in erroneous classification of sleep-wake behaviour in adults and in children (Bigué et al., 2020; Meltzer et al., 2012; Quante et al., 2018).

Estimates of sleep variables were scored according to ActiLife software using the Sadeh algorithm (Sadeh et al., 1994) using 60 second epochs. The Sadeh algorithm has been validated against polysomnography in a population of 10 to 25 year-olds, showing agreement rates in sleep-wake detection between 91-93% (Sadeh et al., 1994). Accelerometry data was refined using logbook reports of when participants reported falling asleep and waking up. One person was responsible for cleaning and scoring of sleep data.

Sleep quality lacks an established definition in the literature, rather it is a term that represents how ‘well’ someone slept overall. Often sleep quality is inferred from multiple characteristics of a persons sleep (Krystal & Edinger, 2008). Five actigraph-derived sleep parameters were used to assess sleep quality in the current study: 1) total sleep time (TST), defined as the total amount of hours asleep after sleep onset; 2) sleep efficiency (SE), defined as ratio between a person's TST and their total time in bed (amount of time between when the participant indicated they went to sleep and woke up), expressed as a percentage; 3) wake after sleep onset (WASO), defined as the number of minutes scored as being awake after sleep onset; 4) number of arousals per hour (NOA), defined as the number of different arousal episodes as scored by the algorithm per hour; and 5) average arousal length (AAL), defined as the average length, in minutes, of all arousal episodes. Collectively, these variables provide information about a person's sleep and arousal behaviour, allowing for inferences about sleep characteristics and overall sleep quality (Shrivastava et al., 2014).

2.35 Statistical Methods

All statistics were performed using STATA/IC 15.1. The normality of sleep quality data was assessed using visual inspection and Shapiro-Wilks tests. Some sleep quality parameters were slightly skewed, however mean and median values did not greatly differ. To allow for appropriate comparisons with published normal sleep estimates, participant sleep data were summarized as means and 95% confidence intervals (95% CI). The threshold for statistical significance across all analyses was two-tailed and set at $p < 0.05$.

To account for inter-participant variation in the number of nighttime observations due to variation in recruitment timelines and missing data, analytical weighted group means for each sleep parameter were calculated for each week. Weekly sleep parameter outcomes were weighted using the number of nighttime observations available for each participant for a given week. To determine if sleep in concussed participants differed from normal healthy populations, the mean TST, SE, and WASO of participants were compared with published values of normal actigraphy data for healthy children and adolescents using single sample t-tests. Family-wise

Bonferroni corrections for multiple comparisons were performed. The normal data used for comparisons was obtained from a meta-analysis and systematic review of 87 studies involving actigraphy-based measurement of sleep in healthy children and adolescents, published by Galland et al., 2018 **(Table A1)**. Changes in sleep parameter trajectories were assessed descriptively, informed using evidence from weekly sleep parameter estimates and graphical illustrations of daily mean sleep parameter outcomes.

Linear multivariate mixed effects regression modelling was used to identify factors associated with changes in objective post-concussion sleep quality over time. Sex, age, initial PCSI score, concussion history (no previous concussions and one or more previous concussions), preinjury sleep complaints, and postinjury sleep complaints were explored simultaneously as predictors of sleep quality outcomes. Time since injury was included in mixed effect models to account for variation in the timing of sleep data and to assess the significance of changes in sleep parameters over time. Selection of predictor variables was informed by previous literature that implicates each variable in post-concussion outcomes (Iverson et al., 2017; Zemek, Barrowman, Freedman, Gravel, Gagnon, McGahern, Aglipay, Sangha, Boutis, Beer, Craig, Burns, Farion, Mikrogianakis, Barlow, Dubrovsky, Meeuwisse, Gioia, Meehan, Beauchamp, Kamil, Grool, Hoshizaki, Anderson, Brooks, Yeates, Vassilyadi, Klassen, Keightley, Richer, De Matteo, et al., 2016) or are associated with subjective sleep reporting. Separate multivariate mixed models were developed, using each sleep quality measure (TST, SE, WASO, NOA, and AAL) as a seperate primary outcome variable. To consider baseline variation and variation in sleep quality trajectory, both random intercept and random intercept with random slope mixed effects models were developed and compared for each sleep quality variable. To ensure integrity of mixed effects regression assumptions, diagnostics tests included examination of potential outliers as well as examination collinearity between predictor variables. Appropriate steps were performed and reported if assumptions were violated.

2.4 Results

Sleep data was available for 106 participants. 25 participants were excluded because they did not have sleep data within 4 weeks of their injury. After outlier inspection, the actigraphy data of 2 participants were deemed to be outliers and were removed from further analyses. 79 participants were used in final analyses. Due to variation in recruitment timelines and missing data the average number of nighttime observations obtained per person was 10.1 days, ranging from 1 day of information to 28 days. Descriptive results are displayed in **Table 1**.

2.41 Sleep Quality Outcomes in Children

The mean TST of child participants (ages 5-11) was less than, but not statistically different than the normal TST estimate across all 4 weeks **(Table 2)**. Moderate increases in mean TST estimates up to 23.6 minutes were observed throughout recovery relative to week 1 **(Table 2, Fig. 1a)**. The mean SE of concussed participants was significantly lower than the normal SE estimate for healthy children and adolescents for all 4 weeks of recovery **(Table 2)**. The greatest disparity between participant and normal SE estimates occurred during the first week of recovery, differing by 9.9%. Mean estimates of SE improved each subsequent week, increasing by 5.7% from week 1 to week 4. This trend is apparent when graphically illustrated **(Figure 1a)**. The mean WASO duration of participants was significantly and substantially greater than the normal WASO estimate across all 4 weeks, with differences ranging from 41.2 to 59.9 minutes **(Table 2)**. Mean participant WASO declined with each subsequent week **(Table 2)**. This decrease in WASO trajectory is appreciated graphically in **Fig. 1a**. The mean NOA of participants fluctuated between 3.1 and 3.5 arousals per hour throughout the 4 weeks of recovery with no real observable trends over time **(Table 2, Fig. 1a)**. The mean AAL of participants decreased slightly with each subsequent week **(Table 2)**. When assessed graphically, a small decrease in AAL over time is observed **(Fig 1a)**.

2.42 Sleep Quality Outcomes in Adolescents

Mean estimates of TST in adolescents (ages 12-18) were statistically longer than the normal TST estimate across all 4 weeks **(Table 3)**. The mean TST of participants increased each subsequent week throughout recovery **(Table 3)**. This trend is not as apparent when illustrated graphically **(Fig. 1b)**. The mean SE of participants was significantly lower than the normal SE estimates across all 4 weeks **(Table** 3**)**. The greatest discrepancy between participant and normal SE estimates was observed during week 1 of recovery, differing by 8.7%. Mean SE estimates demonstrate small improvement throughout recovery, relative to week 1, with the greatest increase in mean SE of 1.9% occurring during week 3. Increases in SE trajectory are observed when graphically illustrated in **Fig. 1b**. Mean WASO duration of participants was statistically and substantially longer than normal WASO estimates across all 4 weeks, with differences ranging from 42.2 to 56.5 minutes **(Table 3)**. Relative to week 1, WASO estimates decreased until week 3, followed by a moderate increase during week 4 (**Table 3**). When illustrated graphically, a slight U-shaped trend in WASO duration is apparent **(Fig. 1b)**. Mean NOA remained relatively constant throughout 4 weeks of recovery. No discernible trends in participant NOA were appreciated numerically or graphically throughout the 4 weeks measured **(Table 3,**

2.43 Predictors of Objective Post-Concussion Sleep Quality

Demographic, preinjury, postinjury, and time-related factors were assessed as predictors of each sleep parameter in separate multivariate random-intercept mixed effects models. Results are displayed in **Table 4**. In the model assessing TST, participant age was significantly predictive of TST ($p = 0.003$), indicating that older age was associated with decreased TST. Age was not significantly associated with other sleep parameters. Days since injury was significantly and positively associated with SE outcomes ($p = 0.047$), indicating significant positive change in SE over time. In models of WASO and AAL, female sex was significantly associated with longer WASO duration ($p = 0.025$) and AAL ($p = 0.044$), respectively. Female sex was also strongly, but not significantly associated with negative SE outcomes ($p = 0.071$). No significant predictor variables were associated with NOA. Factors including history of concussion, initial PCSS score, as well as preinjury and postinjury sleep complaints were not statistically associated with any objective sleep parameter.

2.5 Discussion

To our knowledge, this is the first study to describe trends in objective sleep quality in children and adolescents across the first 4 weeks of recovery post concussion. Results demonstrate that when compared with healthy normal actigraphy sleep estimates, adolescent participants experience significantly longer TST and both child and adolescent participants experience significantly lower SE and significantly longer WASO duration. These sleep parameters did not return to normal after 4 weeks of recovery. However, some discernable trends of improvement are observable for measures of TST, SE, WASO, and AAL in child participants and in measures of SE and WASO in adolescent participants, although only SE was found to statistically increase with time throughout recovery ($p = 0.047$). Using multivariate mixed effects modelling, older age was found to be a significant predictor of shorter TST, time since injury was significantly associated with improvements in SE, and female sex was significantly associated with longer WASO and AAL and was non-significantly, but somewhat related to poorer SE. Both subjective preinjury and postinjury sleep complaints, as well as history of concussion and initial symptom score, were not associated with sleep parameters. Collectively, these results suggest that objective sleep quality is adversely affected after concussion, particularly in females, but shows some trends towards improvements with time.

Consistent with our hypotheses, the results from this study indicate that objective sleep quality parameters are significantly affected in the weeks following concussion for both children and adolescents. In particular, participants' WASO duration appeared to be most substantially impacted, where child and adolescent participants were found to have between 41.2-59.9 minutes greater WASO duration than normal estimates. This likely explains why participants experienced significantly poorer SE throughout recovery. This provides evidence that youth with concussion experience alterations in their sleep, resulting in greater periods of wakefulness throughout the night, impairing their SE, and ultimately leading to poorer overall objective sleep quality.

These results are similar with findings by Tham et al., 2015, who observed that children and adolescents with concussion experienced significantly poorer SE and greater WASO duration 3 to 12 months post-injury when compared to healthy controls. However, the current study expands upon these findings, supporting that objective sleep quality is altered within the first 4 weeks of concussion recovery as well. In conjunction with the results observed by Tham et al., 2015, these findings provide evidence that concussion results in acute and longer-term decrements in sleep quality post concussion. Considering the importance of sleep in the maintenance of cognitive, mental, and physical health, this may have implications in the recovery from concussion in youth (Kenzie et al., 2018).

However, the results found in this study are in disagreement with studies examining older populations, which have found that objective sleep quality was not significantly impacted by concussion in adolescents, young adults, (Gosselin et al., 2009) or adults (Allan et al., 2017;

Mantua et al., 2018). However, most of these studies' results are interpreted from only a few nights worth of sleep data. From **Figure 1**, it is apparent that there is tremendous day to day variability in the sleep quality outcomes. It is likely that without sufficient longitudinal sleep data collection, these results may be affected by daily variation, and therefore are less likely to find significant differences (Newell et al., 2012). By assessing sleep quality over several nights, the present study more appropriately accounts for day-to-day variation and provides a more accurate reflection of post-concussion sleep trends.

Additionally, as hypothesized, several sleep parameters showed trends of improvement throughout recovery, particularly in child participants. For both child and adolescent participants, the greatest discrepancies between SE and WASO sleep parameters and normal estimates occurred during week 1. SE and WASO estimates in subsequent weeks more closely resembled normal data estimates. Furthermore, SE was found to statistically increase with time since injury. These results likely demonstrate improvements in objective sleep and a return to normal sleep quality as participants recovered from their concussion.

Child participants were found to have subsequent decreases in the duration of AAL relative to week 1. This appears to indicate that children progressively experienced less wakefulness throughout the night, representing improvements in wake behaviour and sleep quality throughout recovery. Longitudinal trends of improvement were less pronounced in adolescent participants. While improvements in SE and WASO were appreciable, no discernable trends were observed for NOA or AAL. Additionally, a slight change in the direction of a respective trend was observed during week 4 for several sleep parameters in adolescent participants, possibly indicating a change in sleep quality trajectory. Although, more sleep data beyond 4 weeks is required to assess these changes more appropriately.

While these results appear to indicate that improvement seen in sleep quality trajectories differ between children and adolescents, it should be noted that age was not found to be significantly associated with sleep parameter outcomes other than TST. Future research should be directed towards clarifying if, and how, objective sleep quality trajectories differ between children and adolescents throughout recovery from concussion.

It is unclear from this study whether these sleep quality trends continue beyond 4 weeks or if sleep quality issues resolve along with, or independently from other concussion symptoms. Measures of SE and WASO still greatly differed from normal estimates even after 4 weeks, which is considered to represent the expected recovery time frame in children and adolescents (McCrory et al., 2017b). However, it should be noted that this study did not account for the baseline sleep estimates of participants prior to their concussion. Therefore, direct comparisons between participants pre- and post-concussion sleep quality could not be made to determine if participants truly did, or did not, return to normal. However, comparisons made with values published by Galland et al., 2018 suggest that sleep quality issues do persist up to 4 weeks post concussion. These results appear consistent with other studies that found that objective sleep quality remains impaired months after concussion (Tham et al., 2015). Future research should examine sleep quality outcomes beyond 4 weeks considering baseline sleep values to identify if, and or when sleep quality returns to normal after concussion.

This study also provide evidence that certain demographic factors are associated with objective post-concussion sleep quality. Results demonstrate that age was negatively predictive of TST. This is consistent with the majority of sleep literature, which finds that TST naturally declines as people age from childhood into adolescents (B. C. Galland et al., 2018; Maslowsky & Ozer, 2014; J. A. Williams et al., 2013b). Age was not significantly associated with other sleep quality measures. It was also discovered that female sex was associated with significantly longer WASO and AAL. While non-significant, female sex also appeared to be somewhat negatively associated with SE. This suggests that females may experience poorer objective sleep quality following concussion. This observation may be congruent with other patterns of concussion recovery, which find that female sex is a risk-factor for prolonged recovery (Iverson et al., 2017; Marshall et al., 2019; Zemek et al., 2016). Perhaps, increased susceptibility to sleep quality issues in females is associated with longer recovery outcomes. Although, more research is needed to comment on the association or directionality of this relationship.

Another interesting observation of this study is that both preinjury and postinjury subjective sleep complaints, as measured by self report PCSS, were not associated with objective sleep quality outcomes. Consistent with other research (Allan et al., 2017; Berger et al., 2017; Gosselin et al., 2009), these results provide evidence that supports a difference between objective and subjective sleep quality. These results further suggest that subjective and objective sleep quality are not capturing the same phenomena and should be interpreted carefully.

2.51 Limitations

These results should be interpreted in consideration of several limitations. Firstly, averaging sleep parameter outcomes into weekly time-blocks may not be the most appropriate method to capture shorter-term changes in sleep quality. However, this was performed to allow for comparisons between participant outcomes and normal estimates to be made throughout recovery.

Secondly, statistical comparisons of sleep parameters were made without a control group. Rather, outcomes were compared with normal estimates synthesized in a systematic review and meta-analysis using data from several studies and age ranges. Methodological and age-related differences between studies may contribute to greater variance in estimates of normal sleep quality. Additionally, given that only means and confidence intervals of sleep parameter estimates were provided in the study by Galland et al., 2018, comparisons between participant data and normal data were performed using sample means, despite some sleep data being slightly skewed. However, given the lack of established age-relevant normal actigraphy data and without a control group, participant data was compared with the most appropriate and most recent normal sleep quality estimates available.

Thirdly, the amount of nighttime observations collected for each participant was unequal and often only quantified sleep quality for a part of their recovery. In addition, participants were recruited for study at variable times in their recovery. Therefore, not all participants had sleep data available for the same time periods. Although, analyses were weighted and controlled to account for the strength of each participants data and for the amount of time spent between injury and when the sleep data was collected. Future studies should aim to diligently track sleep quality outcomes longitudinally from the time of injury, until, and beyond recovery, to assess how objective sleep parameters change more comprehensively. A control cohort should also be implemented to more appropriately compare the sleep quality of concussed and healthy children and adolescents.

Lastly, sleep parameter outcomes did not take daytime sleep behaviour into consideration. Following concussion, daytime sleepiness is common and has been shown to affect nighttime sleep behaviour and shift circadian rhythm cycles (Mosti et al., 2016). Consideration to the daytime sleep behavior of participants may better explain some of the sleep trends observed in participants. Interpretation of sleep parameter outcomes should be done with consideration to this limitation.

Additional consideration should be made to the limitations of actigraph-based sleep assessment. Given that actigraphy generally has poor specificity to detect wakefulness (Bigué et al., 2020; Meltzer et al., 2012; Quante et al., 2018), sleep outcomes may not accurately reflect true sleep activity, particularly in measures of SE and WASO. While actigraphy is considered a valid measurement of sleep activity after traumatic injury (Bigué et al., 2020), the strength of conclusions should be consecrate of these limitations.

2.52 Conclusion

This study provides evidence that several parameters of objective sleep quality are affected after concussion in children and adolescents. Some parameters of sleep quality show trends of improvement throughout recovery, particularly in children. However, effected parameters do not return to normal as measured against normative data for age, within 4 weeks of injury. Female sex is significantly associated with longer WASO duration and AAL. Subjective sleep complaints were not associated with objective sleep parameters. Considering that sleep quality is affected by concussion, future studies should continue to examine objective sleep quality trends beyond four weeks and examine the relationship between sleep quality and recovery outcomes.

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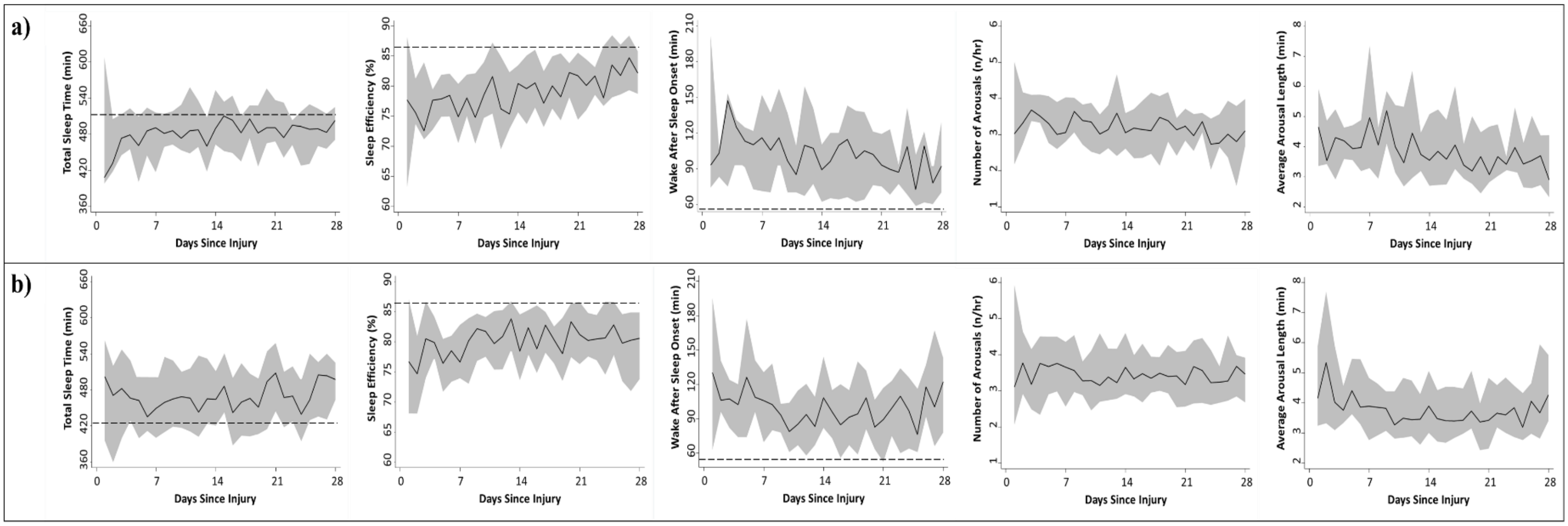

Figure 1. Daily actigraphy estimates demonstrating sleep parameter trajectories and day-to-day variation throughout 4 weeks of recovery, displayed with 95% confidence intervals. a) Daily sleep parameter estimates for child participants across 1 week (n = 17), 2 weeks (n = 21), 3 weeks (n = 18), and 4 weeks (n = 13) post-concussion. **b)** Daily sleep parameter estimates for adolescent participants across 1 week (n = 30), 2 weeks (n = 42), 3 weeks (n = 38), and 4 weeks (n = 35) post-concussion. Normal sleep parameter estimates of healthy children and adolescents are displayed for total sleep time (TST), sleep efficiency (SE), wake after sleep onset (WASO), represented by the dashed line.

Table 1. Participant characteristics.

	Participant Sample (n = 79)
Age: mean (range)	12.5 (5.96, 17.73)
Sex: n (%)	
Male	40 (51.0%)
Female	39 (49.0%)
Number of Concussions: n (%)	
None	57 (72.1%)
One or more	22 (27.9%)
Initial PCSS Score: med. (2nd, 3rd qrt)	30.0 (15.0, 56.0)
Mechanism of Injury: n (%)	
Sports	58 (73.4%)
Recreation (Non-Sport Related)	13 (16.5%)
Other	8 (10.1%)
Premorbid Conditions: n (%)	
Anxiety	9 (11.4%)
Depression	3 (3.8%)
Learning Disability	10 (12.7%)
Attention Deficit Hyperactivity Disorder	8 (10.1%)
Developmental Disorder	1 (1.3%)
Headaches	16 (20.3%)
Sleep Disorder	1 (1.3%)
Preinjury Sleep Complaints: n (%)	17 (21.5%)
Postinjury Sleep Complaints: n (%)	38 (48.1%)

PCSS = Post-Concussion Symptom Scale

Table 2. Weekly actigraphy sleep parameter outcomes for child participants (n = 24).

		Participant Actigraphy Outcomes	Normative Actigraph Value	Comparison of Normative and Participant Means	
Actigraph Sleep Parameter	**n* (# of obs.)ǂ**	**Weighted Mean (95% CI**	**Mean (95% CI)**	**Difference**	**p-value**
Total Sleep Time (minutes)			494.4 (469.8, 519.0)		
1 Week	17 (81)	469.9 (441.5, 498.3)		-24.5	0.444
2 Weeks	21 (132)	481.3 (458.0, 504.7)		-13.1	0.884
3 Weeks	18 (111)	493.5 (44.8, 512.2)		-0.9	1.000
4 Weeks	13 (59)	487.8 (463.7, 512.0)		-6.6	1.000
Sleep Efficiency (%)			86.3 (84.4, 88.2)		
1 Week	17 (81)	76.4 (73.0, 79.8)		-9.9	**<0.001**
2 Weeks	21 (132)	77.8 (75.0, 80.6)		-8.5	**<0.001**
3 Weeks	18 (111)	79.6 (77.0, 82.3)		-6.7	**<0.001**
4 Weeks	13 (59)	82.1 (79.7, 84.5)		-4.2	**0.006**
Wake After Sleep Onset (minutes)			55.0 (43.0, 68.0)		
1 Week	17 (81)	116.7 (99.3, 134.1)		61.7	**<0.001**
2 Weeks	21 (132)	109.6 (95.3, 123.8)		54.6	**<0.001**
3 Weeks	18 (111)	104.1 (84.5, 123.8)		49.1	**<0.001**
4 Weeks	13 (59)	90.9 (77.4, 104.2)		35.3	**<0.001**
Number of Arousals (n/ hour)			N.A.		
1 Week	17 (81)	3.5 (3.1, 3.8)			
2 Weeks	21 (132)	3.3 (3.1, 3.5)			
3 Weeks	18 (111)	3.2 (2.9, 3.6)			
4 Weeks	13 (59)	3.1 (2.7, 3.6)			
Average Arousal Length (minutes)			N.A.		
1 Week	17 (81)	4.5 (3.8, 5.3)			
2 Weeks	21 (132)	4.3 (3.8, 4.9)			
3 Weeks	18 (111)	4.1 (3.4, 4.8)			
4 Weeks	13 (59)	3.8 (3.2, 4.4)			

*: the number of participants with sleep data.

ǂ: the number of nighttime observations used to generate the calculation.

Table 3. Weekly actigraphy sleep parameter outcomes for adolescent participants (n = 55).

		Participant Actigraphy Outcomes	Normative Actigraph Value	Comparison of Normative and Participant Means	
Actigraph Sleep Parameter	**n* (# of obs.)‡**	**Weighted Mean (95% CI**	**Mean (95% CI)**	**Difference**	**p-value**
Total Sleep Time (minutes)			421.2 (406.2, 436.2)		
1 Week	30 (142)	462.0 (438.1, 485.9)		40.8	**0.005**
2 Weeks	43 (241)	463.5 (447.5, 479.5)		42.3	**<0.000**
3 Weeks	38 (232)	464.6 (446.8, 482.3)		43.4	**<0.000**
4 Weeks	35 (197)	467.8 (448.2, 487.5)		46.6	**0.002**
Sleep Efficiency (%)			86.3 (84.4, 88.2)		
1 Week	30 (142)	77.0 (74.9, 9.0)		-9.3	**<0.001**
2 Weeks	43 (241)	79.5 (77.8, 81.2)		-6.8	**<0.001**
3 Weeks	38 (232)	79.8 (78.3, 81.4)		-6.5	**<0.001**
4 Weeks	35 (197)	79.3 (77.6, 81.0)		-7.1	**<0.001**
Wake After Sleep Onset (minutes)			55.0 (43.0, 68.0)		
1 Week	30 (142)	113.5 (101.2, 125.9)		58.5	**<0.001**
2 Weeks	43 (241)	102.1 (91.9, 112.3)		47.1	**<0.001**
3 Weeks	38 (232)	98.6 (88.6, 108.6)		43.6	**<0.001**
4 Weeks	35 (197)	108.1 (96.3, 119.8)		53.1	**<0.001**
Number of Arousals (n/ hour)			N.A.		
1 Week	30 (142)	3.6 (3.3, 4.0)			
2 Weeks	43 (241)	3.5 (3.2, 3.8)			
3 Weeks	38 (232)	3.5 (3.2, 3.7)			
4 Weeks	35 (197)	3.5 (3.2, 3.8)			
Average Arousal Length (minutes)			N.A.		
1 Week	30 (142)	4.8 (4.1, 5.5)			
2 Weeks	43 (241)	4.0 (3.7, 4.3)			
3 Weeks	38 (232)	4.0 (3.5, 4.4)			
4 Weeks	35 (197)	4.2 (3.9, 4.6)			

*: the number of participants with sleep data.
‡: the number of nighttime observations used to generate the calculation.

Table 4. Results from random intercept multivariate mixed-effects regression models examining the relationship between predictor variables and sleep parameters for all participants (n = 79).

	Total Sleep Time		Sleep Efficiency		Wake After Sleep Onset		Number of Arousals		Average Arousal Length	
Predictor Variables	**β-Coef. (95% CI)**	**p-value**	**β-Coef. (95% CI)**	**p-value**	**β-Coef. 0(95% CI)**	**p-value**	**β-Coef. (95% CI)**	**p-value**	**β-Coef. (95% CI)**	**p-value**
Days since injury	-0.35 (-0.97, 0.28)	0.276	0.06 (0.00, 0.12)	**0.047**	-0.24 (-0.63, 0.15)	0.226	-0.04 (-0.10, 0.03)	0.272	-0.01 (-0.03, 0.01)	0.186
Age	-6.60 (-10.97, -2.22)	**0.003**	0.01 (-0.43, 0.44)	0.975	-0.21 (-2.75, 2.32)	0.868	0.06 (-0.39, 0.51)	0.792	-0.01 (-0.11, 0.08)	0.821
Female (vs. male)	-3.14 (-28.63, 22.35)	0.809	-2.34 (-4.89, 0.20)	0.071	16.8 (2.06, 31.60)	**0.025**	0.72 (-1.89, 3.32)	0.590	0.57 (0.02, 1.13)	**0.044**
History of concussion	23.10 (-2.22, 48.43)	0.074	0.02 (-2.51, 2.54)	0.990	5.01 (-9.70, 19.72)	0.505	0.85 (-1.74, 3.44)	0.522	0.06 (-0.49, 0.62)	0.820
Initial PCSS score	0.06 (-0.48, 0.60)	0.823	0.03 (-0.03, 0.08)	0.351	-0.18 (-0.49, 0.14)	0.271	-0.04 (-0.09, 0.02)	0.183	0.00 (-0.01, 0.01)	0.828
Preinjury Sleep Complaints	-11.10 (-40.84, 18.64)	0.464	-0.57 (-3.54, 2.39)	0.705	0.52 (-16.75, 17.80)	0.953	-0.64 (-3.68, 2.40)	0.680	-0.02 (-0.68, 0.64)	0.954
Postinjury Sleep Complaints	12.94 (-14.82, 40.71)	0.361	-2.18 (-4.95, 0.59)	0.123	15.34 (-0.77, 31.46)	0.062	1.77 (-1.07, 4.60)	0.222	0.50 (-0.11, 1.11).	0.107

2.7 Appendix

Table A1. Normal pooled mean actigraphy estimates of sleep parameters in healthy children and adolescents, published in a systematic review and meta-analysis of 87 studies by Galland et al., 2018.

Sleep Quality Variable	Ages	Number of Datasets	Pooled Sample Size	Pooled Mean Estimate	95% CI
Total Sleep Time (min.)	6-8 years	10	815	494.4	(469.8, 519.0)
Total Sleep Time (min)	15-18 years	9	1536	421.2	(406.2, 436.2)
Sleep Efficiency (%)	3-14 years	23	1702	86.3	(84.4, 88.2)
Wake After Sleep Onset (mins.)	3-18 years	28	975	55.0	(43.0, 68.0)

CHAPTER THREE:

DOES SLEEP QUALITY INFLUENCE RECOVERY OUTCOMES AFTER POST-CONCUSSIVE INJURY IN CHILDREN AND ADOLESCENTS?

3.1 Abstract

Introduction: Sleep disturbances are commonly experienced among children and adolescents with concussion. Given the important role of sleep in the maintenance of physical, cognitive, and mental health, post-concussion sleep quality may be related to concussion recovery outcomes.

Objectives: This study seeks to determine if sleep quality is associated with; 1) time to return to school (RTS) and return to activity (RTA); and 2) quality of life (QOL) and depression symptomology outcomes in children and adolescents following concussion.

Methods: The objective sleep quality of 65 children and adolescents (ages 5-18) with concussion was evaluated using actigraphy-based measurement of five objective sleep parameters: total sleep time, sleep efficiency, wake after sleep onset, average arousal length, and number of arousals per hour. Participants sleep quality was assessed in weekly increments across 4-weeks of recovery. QOL and depression symptomatology were assessed one week after recruitment and at 3-months post-recovery or 6-months post recruitment, whichever came first, using the Kidscreen-52 (KS-52) and Children's Depression Inventory (CDI-2), respectively. Univariate Cox-proportional hazards models were used to assess the association between weekly sleep parameter outcomes and time to reach RTS and RTA. Spearman rank correlations were used to determine the association between weekly sleep parameter outcomes and KS-52 and CDI-2 scores as well as changes in KS-52 and CDI-2 scores.

Results: Weekly sleep parameter outcomes were not significantly associated with time to RTS or RTA. Weekly sleep parameters were not meaningfully correlated with final KS-52 scores, CDI-2 scores, KS-52 difference scores, or CDI-2 difference scores.

Conclusions: Objective post-concussion sleep quality may not be associated with recovery duration or post-concussion QOL and depression symptomatology outcomes. Other factors associated with prolonged recovery may be more important predictors of recovery outcomes than objective sleep quality.

3.2 Introduction

Concussions are common in children and adolescents (Baldwin et al., 2018; Guerriero et al., 2012; Meehan et al., 2011). Typically, youth recover from their concussion in approximately 4 weeks (McCrory et al., 2017) and return to school and physical activity in approximately 35 and 38 days post-injury, respectively (DeMatteo et al., 2019). However, nearly 30% of children and adolescents with concussion experience persistent symptoms beyond 4 weeks (Zemek, Barrowman, Freedman, Gravel, Gagnon, McGahern, Aglipay, Sangha, Boutis, Beer, Craig, Burns, Farion, Mikrogianakis, Barlow, Dubrovsky, Meeuwisse, Gioia, Meehan, Beauchamp, Kamil, Grool, Hoshizaki, Anderson, Brooks, Yeates, Vassilyadi, Klassen, Keightley, Richer, De Matteo, et al., 2016). Concussion symptoms can have significant adverse effects and present considerable challenges for children and adolescents. Evidence suggests that some youth experience decrements in several physical and psychological dimensions of their quality of life (QOL) (DeMatteo et al., 2014; Fineblit et al., 2016; Moran et al., 2012; Novak et al., 2016; Russell et al., 2019) and may be more likely to develop depression-like symptoms or be diagnosed with clinical depression following concussion (Chrisman & Richardson, 2014; Manley et al., 2017; Stazyk et al., 2017).

Identifying factors associated with recovery length and post-concussion outcomes may be important for developing more comprehensive management strategies that better target youth who are at-risk for developing persistent post-concussion issues. Current literature supports that female sex, adolescent age, concussion history, initial symptom score, as well as premorbid mental health and headaches/migraines are significant predictors of persistent symptoms and delayed recovery in children and adolescents (Marshall et al., 2019; Zemek et al., 2016). There is growing evidence that also supports an association between post-concussion sleep quality and recovery outcomes following a concussion (Bramley et al., 2017; Chung et al., 2019; Hinds et al., 2016; Hoffman et al., 2017, 2019). However, research related to the topic is relatively new and few studies have comprehensively examined this relationship, especially in pediatric populations.

Following concussion, children and adolescents frequently complain about sleep issues (Gagner et al., 2015), with studies finding that approximately 27-34% of youth with concussion self-report experiencing some form of sleep disturbance (Bramley et al., 2017; Chung et al., 2019). Persons with post-concussion sleep disturbances are known to experience impaired sleep quality that can result from reduced sleep duration or continuity, sleep timing alterations due to circadian rhythm disorders, alterations in sleep architecture (i.e. sleep stages), or other sleep disorders such as insomnia (Wickwire et al., 2016b). Studies examining the effects of impaired sleep consistently demonstrate a strong relationship between sleep and the maintenance of cognitive, mental, and physical health (Chaput et al., 2016). In healthy pediatric populations, sleep issues are associated with poorer academic performance (Dewald et al., 2010), mood and mental health issues (Alvaro et al. , 2013; Kouros & El-Sheikh, 2015), impaired physical performance (Taylor et al., 2016; Watson, 2017), and increased risk of injury (Gao et al., 2019; Milewski et al., 2014).

Following concussion, some research has shown that poor subjective (self report) sleep quality is associated with greater symptom severity (Chung et al., 2019; Kostyun et al., 2015), as well as elevated anxiety ratings and depression scores in children and adolescents with concussion (Chung et al., 2019). In a prospective cohort study of 517 children and adolescents by (Chung et al., 2019), when compared to ‘good sleepers’, participants who were considered ‘poor sleepers’ using the Pittsburgh Sleep Quality Index took over two weeks longer to be cleared by a clinician to return to play. Similar results were found in a retrospective chart review of concussed adolescents by (Bramley et al., 2017), who observed that self-reported SD was associated with a 3- to 4- fold increase in recovery time. While these studies provide invaluable evidence in support of a relationship between subjective sleep quality and recovery from pediatric concussion, they cannot comment on the directionality of this relationship nor did they account for the effects of additional factors such as age, sex, and initial symptom score. Therefore, there is still a need for more research that examines the causal relationship between sleep and concussion outcomes.

Furthermore, these studies have only demonstrated a relationship between sleep and recovery using subjective assessments of sleep quality. Evidence from Berger et al., 2017 demonstrates that subjective questionnaires poorly correlate with objective sleep quality estimates after pediatric concussion. This suggests that both measurements may assess different aspects of sleep quality. Thus, both types of measurement must be researched and used to comprehensively evaluate sleep quality following concussion. Evidence linking objective sleep quality to recovery and post-concussion outcomes is significantly lacking. Only one recent study has examined this relationship through objective measures. Using actigraphy in a small group of 22 concussed college students, Hoffman et al., 2019 found that some actigraphy-derived sleep variables, particularly in the mid- to later stages of recovery, were correlated with length of time to reach symptom resolution. Although, given the small sample size, lack of control variables, and weaker analysis techniques, conclusions drawn from this study are limited. No known studies that have examined this relationship in children or adolescents.

While polysomnography is considered the gold standard of objective sleep measurement, actigraphy offers a valid and feasible means to measure sleep activity in persons with traumatic injury (Bigué et al., 2020). Using actigraphy to approximate sleep parameters (total sleep time, sleep efficiency, wake after sleep onset, average arousal length, and number of arousals), this study aims to provide evidence describing the relationship between sleep quality and recovery outcomes following pediatric concussion. Specifically, the objectives of this study are to determine if objective sleep parameters within the first 4 weeks of recovery are: 1) associated with the number of days to return to school and return to activity in children and adolescence with concussion; 2) correlated with QOL and depression symptomatology outcomes at 3-months post-recovery or 6-months post-injury, as measured by The Kidscreen Questionnaire (52-item) and the Children's Depression Inventory (Version 2), respectively; and 3) correlated with changes in QOL and depression symptomatology outcomes.

3.3 Methods

3.31 Study Design

Analyses were performed using data gathered from a larger prospective cohort study of children and adolescents with concussion examining adherence rates to return to school (RTS) and return to activity (RTA) protocols (DeMatteo et al., 2019). The current study examines actigraphy-based sleep data of participants, collected longitudinally throughout their completion of RTS and RTA protocols.

3.32 Ethical Review

The primary study was approved by the Hamilton Integrated Research Ethics Board at McMaster University. Informed consent was provided by youth ages 16 and older. Children under the age of 15 provided assent and informed consent was obtained from the parent or legal guardian.

3.33 Participants and Procedures

Participants were recruited from the McMaster Children's Hospital and community referrals in Hamilton, Ontario between November 2014 and December 2016. Children and adolescents were included for primary study if: 1) they were between the ages of 5-18 years; 2) had a physician confirmed diagnosis of concussion within the past year; and 3) were still symptomatic at the time of recruitment. Persons with injury that resulted in admission to a pediatric critical care unit, surgical intervention, and or resuscitation were excluded from the study. Participants were included for sleep data analyses if they had available actigraphy sleep data within 28 days of their concussion and had documented RTS and RTA information.

Upon enrollment, research staff explained RTS and RTA protocols to participants. Participants were instructed to follow both protocols to guide their recovery process. At recruitment, participant demographics and injury-related information were collected. Initial symptom presentation, pre-injury subjective sleep complaints and subjective sleep complaints at 1 week post-injury were assessed using the Post-Concussion Symptom Scale (PCSS). Participants with a sleep symptoms rating ≥ 1 on the PCSS 7-point Likert scale were considered to have subjective sleep complaints. Once recruited, participants were provided a sleep logbook and an ActiGraph GT3X wrist monitor (ActiGraphTM; ActiGraph, Pensacola, FL, USA) to measure sleep activity. Participants were instructed to wear their ActiGraph wrist monitors nightly throughout completion of RTS and RTA protocols. Logbooks were used to validate actigraphy data. Daytime activity and sleep data was not incorporated into analyses.

Throughout recovery, participants were automatically prompted to self-report their current stage in the RTS/RTA protocols every 48 hours via REDCap (Research Electronic Data Capture, a browser-based application). Following completion of RTS/RTA protocols, participants were prompted every 2 weeks. KS-52 and CDI-2 outcomes were assessed at CanChild a Childhood Disability research centre at McMaster University, School of Rehabilitation Science, initially within one-week of their enrollment, followed by a final assessment at either 3-months after the participant completed both RTS and RTA protocols or at 6-months post-enrollment, whichever came first. This was to account for participants who did not complete protocols or reach a symptom free state during the 6-month study period.

3.34 Measures

Return to School and Return to Activity

RTS (**Figure A1**) and RTA protocols (**Figure A2**) were developed with consideration of the guidelines presented in the 3rd International Conference on Concussion guidelines (McCrory et al., 2009). Note that RTS and RTA protocols have been updated since the completion of this study (McCrory et al., 2017). Protocols provided sequential stages that guided participants through a step-wise, symptoms-based, recovery strategy in attempts to ensure that participants reached an adequate stage of recovery before returning to normal activities. The RTS protocol used was comprised of 5 stages that progressively increased participants cognitive load, starting from Stage 1, "No School", to Stage 5, "Fully Back to School". Completion of Stage 5 indicates that the participant does not exhibit any school-related concussion symptomatology. The RTA protocol was comprised of 6 stages, progressively increasing the activity level of the participant, starting from Stage 1, “No Activity and Complete Rest”, to Stage 6, “Return to Activity, Sport or Game Play. Completion of Stage 6 indicates that the participant does not exhibit any activity-related concussion symptomatology. Participants were instructed to complete both protocols simultaneously. Completion of RTA and RTS protocols were used to estimate the length of recovery. Time to RTS was calculated as the number of days between injury to self-reported completion of stage 5 of RTS protocols. Time to RTA was calculated similarly, representing the number of days from injury to self-reported completion of stage 6 of RTA protocols.

Kidscreen 52

Quality of life (QOL) describes the overall human wellbeing of a person by assessing several domains of everyday functioning, providing information beyond symptom-focused measures (Berman et al., 2016). The Kidscreen-52 (KS-52) (Ravens-Sieberer et al., 2005a) is a 52-item tool used to assess relevant dimensions of QOL in healthy and chronically ill children and adolescents ages 8-18. Specifically, questions examine ten dimensions of QOL: Physical wellbeing, Psychological wellbeing, Moods ad Emotions, Self-Perception, Autonomy, Parent Relations and Home Life, Financial Resources, Social Support and Peers, School Environment, Social Acceptance (Bullying). Participant responses are totalled separately for each dimension and are converted to T-scores using Rasch analysis. Rasch-corrected T-scores have scale means of 50 and standard deviations of 10, with higher values indicating greater HRQOL. Scores above or below 0.5 standard deviations of the relevant normative mean value indicate clinically ‘noticeable’ differences in QOL. The current study examined the physical and psychological wellbeing outcomes as a measure of QOL.

The KS-52 possesses good to excellent internal consistency (Chronbach’s alpha: 0.77-0.89) and moderate to strong test-retest reliability (0.56-0.77). Convergent and discriminant validity were adequately demonstrated using information from children's and adolescents' mental and physical health (Ravens-Sieberer et al., 2005a). Adequate convergent validity was shown using the Youth Quality of Life Instrument-Surveillance Version 5 (Topolski et al., 2004), the Child Health Questionnaire (Landgraf et al., 1996), and the Child Health and Illness Profile (Starfield et al., 1995).

Children's Depression Index-2

The Children's Depression Index Version 2 (CDI-2; Kovacs, 2011) is a 28-item self-report tool used to measure the extent and severity of depressive symptoms in children and adolescents ages 7-17. Questions evaluate affective, and cognitive motivational features of depression, as well as functional impairment that may result from symptoms of depression. Participants respond to questions using a 3-point scale, where 0 indicates no symptoms present, 1 indicates probable or mild symptoms, and 2 indicates definite or marked symptoms. Participants total raw scores are summative of responses over four sub-scores, meant to reflect two distinct problem categories: negative mood/physical symptoms and negative self-esteem, reflecting emotional problems, and interpersonal issues and ineffectiveness, reflecting functional problems. Raw scores are converted to standardized T-scores using Rasch analysis to assess participant scores on a linear scale while accounting for expected age-dependent differences and unequal difficulty and importance of test items. Standardized T-scores have a mean of 50 and standard deviation of 10, with higher scores indicating greater depression symptomology. Participants are considered to show clinically significant depression symptomology if their total T-score is ≥ 65 (1.5 standard deviations above the mean). The current study examines the total T-score as a measure of depression symptomatology in participants.

The CDI-2 has excellent internal consistency (Cronbach's alpha: 0.73-0.91) and test-retest reliability (0.76-0.92). In a sample of youth with major depressive disorder and healthy matched controls, the CDI-2 demonstrated substantial discriminative validity, correctly classifying 78.3% of participants with 83.2% sensitivity and 73.3% specificity (Kovacs, 2011). The CDI-2 also possesses strong construct validity and moderate to strong convergent validity when compared with the Beck Depression Inventory-Youth version (Beck, Beck, Jolly, & Steer, 2001) and Conner's Comprehensive Behaviour Rating Scale (Conners, 2008), respectively (Kovacs, 2011).

<u>Actigraphy and Sleep Parameters</u>

The ActiGraph GT3X wrist monitor uses accelerometry to capture movement in three planes of motion (vertical, anteroposterior, and mediolateral). Using actigraphy, the sleep activity of participants was monitored longitudinally throughout the night in their natural sleep environment over the course of recovery. Actigraphy provides a valid and reliable way to objectively estimate sleep-wake behaviour in healthy children and adolescents (Meltzer et al., 2012; Sadeh, 2011) and is useful in the examining of sleep after traumatic injury (Bigué et al., 2020). Previous literature demonstrates that actigraphy possess strong sensitivity (detection of true sleep), however measurement is limited by poor specificity (detection of true wakefulness) (Bigué et al., 2020; Meltzer et al., 2012; Quante et al., 2018). Consequently, this can result in the erroneous classification of sleep-wake activity.

Sleep quality is a subjective term that broadly describes how well someone slept overall. Sleep quality lacks an established definition in the literature, thus, determination of sleep quality should consider multiple objective aspects of a persons sleep activity (Krystal & Edinger, 2008). In order to comprehensively describe sleep-wake behaviour for this study, sleep quality was assessed according to five objective sleep parameters: 1) total sleep time (TST), defined as the total amount of minutes spent asleep from sleep onset; 2) sleep efficiency (SE), defined as ratio between a person's TST and their total time in bed (amount of time between when the participant indicated they went to sleep and woke up), expressed as a percentage; 3) wake after sleep onset (WASO), defined as the total number of minutes the subject was scored as awake after sleep onset occurred; 4) average arousal length (AAL), defined as the average length, in minutes, of all arousal episodes; and 5) number of arousals per hour (NOA), defined as the number of different arousal episodes as scored by the algorithm per hour. Parameters of objective sleep quality were estimated using ActiLife software and the Sadeh algorithm (A. Sadeh et al., 1994) using 60 second epochs. The Sadeh algorithm has strong validity when compared with polysomnography, showing agreement rates of 91-93% in a sample of participants 10-25 years old (Sadeh et al., 1994). One person was responsible for cleaning and scoring actigraphy data.

3.35 Statistical Methods

All statistical analyses were performed using STATA/IC 15.1. Normality was assessed using histograms and Shapiro-Wilks tests. Time to RTS, time to RTA, KS-52 T-Scores, and CDI-2 T-Scores were not normally distributed and were reported as their median (2^{nd}, 3^{rd} quartile). The Berlin 5^{th} Consensus Statement on concussion acknowledges that the expected duration for symptoms recovery is approximately 4 weeks for children and adolescents (McCrory et al., 2017). Given this, and the availability of participant sleep data, the sleep quality of participants was assessed over a 4-week period. Sleep parameter estimates for each participant were averaged for each week. Given the data available, participants were required to have at least 3 nights of sleep data for a given week to be included in analyses for that respective week. The threshold for statistical significance across all analyses was two-tailed and set at $p \leq 0.05$.

Time to RTS and time to RTA were assessed separately. Survival analyses were conducted using univariate Cox proportional hazards models to determine the association between sleep quality parameters and time to RTS and RTA. Participants who did not report reaching Stage 5 of RTS protocols or Stage 6 of RTA protocols throughout their duration in the study were considered ‘unrecovered’ and were censored in the respective analysis. Including censored data was necessary to prevent bias of increased time to RTS and RTA in probability estimates. To account for significant collinearity between sleep parameters, the association between recovery length and sleep parameter estimates were assessed individually for each of the 4-weeks. The effect of sleep on time to RTS and time to RTA was explored through hazard ratios. Hazard ratios represent the relative probability of completing RTS or RTA protocols at any given time given a certain sleep parameter outcome.

T-Scores were calculated for KS-52 and CDI-2 outcomes for participants initial and final assessment. Difference scores were calculated for KS-52 and CDI-2 measures by subtracting participants initial T-Score from their Final T-Score. Sleep parameter estimates for each week were correlated with participants final KS-52 and CDI-2 T-scores as well as KS-52 and CDI-2 difference scores using Spearman rank correlations. Bonferroni corrections for multiple comparisons were performed to account for multiple comparisons.

3.4 Results

Data from 106 participants were available for analysis. 25 participants did not have sleep data within the first 4-weeks, 4 participants did not have more than 3 nights of sleep data, and sleep data from 2 participants were considered outliers and were removed from further analyses. Ten participants were missing self-reported RTS and RTA information and were excluded from analyses. The final sample used in analyses included data from 65 participants. Sleep information was obtained for an average of 10.1 ± 6.7 days for all participants. Information regarding participant characteristics are displayed in **Table 1**.

3.41 Return to School and Return to Activity

RTS protocols were completed by 62 (95.4%) participants in a median of 50.0 (30.4, 61.5) days. RTA protocols were completed by 58 (89.2%) participants in a median of 52.5 (35.6, 64.4) days. Univariate Cox proportional hazard modelling was used to assess the relationship between weekly sleep outcomes and time to RTS and time to RTA. The measure of effect between sleep parameters and time to RTS and time to RTA is demonstrated using hazard ratios, displayed in **Table 2**. Hazard ratio values >1.00 represent a shorter time to RTS or RTA with each increase in the value of a respective sleep parameter, and vice versa. All sleep parameters (TST, SE, WASO, NOA, and AAL) were not significantly associated with RTS or RTA duration throughout 4 weeks of recovery (**Table 2**).

While non-significant, longer sleep duration in weeks 2,3, and 4 post-injury was associated with a shorter RTS and RTA duration. For instance, participants had a 27% increased probability reaching RTS (HR: 1.27; 95% CI: 0.89, 1.81; $p = 0.195$) and RTA (HR: 1.27; 95% CI: 0.86, 1.86; $p = 0.237$) with each hour increase in their sleep during week 3. Furthermore, a greater NOA during each of the 4 weeks was associated with a longer RTA duration. Similarly, a greater NOA during weeks 1,3, and 4 post-injury was associated with a longer RTS duration. No other discernable patters between weekly sleep parameters and time to RTS or RTA are observed.

3.42 Quality of Life

Initial KS-52 outcomes were measured at 1-week post-recruitment, followed by a final assessment at either 3-months after the participant completed both RTS/RTA protocols or at 6-

months post-enrollment, whichever came first. Eight participants did not have complete KS-52 information and were excluded from analyses (n = 61). Median initial and final assessment KS-52 T-Scores are displayed along with the median difference score in **Table 3**. Physical and psychological wellbeing scores increased from initial to final assessment by a median of 14.2 points and 8.2 points, respectively, representing improvements in QOL over time.

Spearman rank correlation coefficients between sleep parameters and final KS-52 T-scores and KS-52 difference scores are displayed in **Table 4**. Week 3 SE was moderately negatively correlated with physical wellbeing (rho: -0.40; p = 0.044). Other sleep parameters were not significantly correlated with physical or psychological wellbeing outcomes, nor were they significantly correlated with physical or psychological wellbeing difference scores.

3.43 Depression Symptomatology

Initial CDI-2 outcomes were measured at 1-week post-recruitment, followed by a final assessment at either 3-months after the participant completed both RTS/RTA protocols or at 6-months post-enrollment, whichever came first. Two participants did not have complete CDI-2 information and were excluded from analyses (n = 63). Median initial and final assessment CDI-2 total T-Scores are displayed along with the median difference score in **Table 3**. Total CDI-2 Scores decreased by a median of -4.0 points, representing a decrease in depression symptomatology over time.

Spearman rank correlation coefficients between sleep parameters and final CDI-2 total T-scores and CDI-2 difference scores are displayed in **Table 5**. Sleep parameters were not significantly associated with final CDI-2 T-scores. Week 1 SE was moderately correlated with decreases in CDI-2 difference scores (rho: -0.43; p = 0.040). No other sleep parameters were correlated with CDI-2 difference scores.

3.5 Discussion

This study is the first to describe the relationship between objective post-concussion sleep quality and recovery outcomes in children and adolescents. The results from survival analysis data indicate that sleep parameters within the first 4 weeks of recovery are not significantly associated with the length of time children and adolescents required to return to school (RTS) or return to activity (RTA). Correlation analyses revealed that sleep parameters were not strongly associated with post-concussion QOL and depression symptomatology. While week 3 SE was moderately negatively correlated with final physical wellbeing outcomes (rho: -0.40; $p = 0.044$), other objective sleep parameters were not significantly associated with final KS-52 scores or changes in KS-52 scores from initial and final assessment. Week 1 SE was moderately associated with decreases in CDI-2 depression symptomatology scores from initial to final assessment (rho: -0.43; $p = 0.040$), however, other sleep parameters were not significantly associated with final CDI-2 scores or changes in CDI-2 scores. Collectively, these findings suggest that sleep quality is not meaningfully associated with recovery length or post-concussion recovery outcomes in children and adolescents.

The results of this study demonstrate that objective sleep parameters were not significantly associated with RTS or RTA duration, suggesting that objective sleep quality is not a significant predictor of concussion recovery length in children and adolescents. These results differ from previous research from Hoffman et al., 2019, who observed a significant positive correlation between WASO and days to symptomatic and a negative correlation between SE and days to asymptomatic in 22 college students. However, this discrepancy may be attributed to the difference in the ages of the study population. Given evidence that recovery length and sleep habits differ between youth and adults (Li et al., 2018; McCrory et al., 2017; Ohayon et al., 2004), sleep may affect recovery in these age populations differently.

It should be noted that some non-significant trends were appreciated between sleep parameters and recovery length. For instance, longer sleep duration following week 1 of recovery was associated with a shorter time to complete RTS and RTA protocols. This may suggest that persons who sleep longer in the post-acute phases of recovery (< 1 week) experience a moderately shorter recovery length. Furthermore, increased nighttime number of arousals appeared to be related with longer RTS and RTA duration. Intuitively, this suggests that persons who experience more nighttime disruption following concussion may be slightly more likely to experience a longer recovery period. However, the magnitude of this relationship was determined to be non-significant and may not be clinically meaningful.

Given that several other factors such as age, sex, concussion history, premorbid mental health, and initial symptom score are associated with length of recovery (Marshall et al., 2019; Zemek et al., 2016), sleep quality alone may not explain recovery outcomes. These factors may be more important predictors of recovery length. Yet, considering the important association between sleep and the miniatous of cognitive, mental, and physical health (Chaput et al., 2016), it is unlikely that sleep quality does not play any role in recovery. Future studies should examine if the addition sleep quality parameters add to the predictive ability of recovery models that consider established predictors of recovery.

The results from KS-52 and CDI-2 outcomes reveal that participants demonstrated improvements in physical and psychological QOL as well as decreases in overall depression symptomatology from initial to final assessment. Correlation analyses demonstrated that most sleep parameters throughout 4 weeks of recovery were not significantly correlated with final KS-52 or CDI-2 scores, nor were they found to be correlated with KS-52 or CDI-2 difference scores.

Week 1 SE was found to be significantly associated with decreases in depression symptomatology scores. However, the magnitude of this relationship was only weak to moderate and there is little supporting evidence from other results that would suggest that there is strong relationship between SE and changes in depression symptomatology. Surprisingly, SE during week 3 of recovery was significantly correlated with poorer final physical wellbeing outcomes. This is an unusual and counterintuitive finding that suggests that better SE is associated with deficits in physical wellbeing. Given the contradictory nature of this finding and the small magnitude of the correlation, again, it is unlikely that this finding is clinically meaningful. Thus, these results appear to indicate that sleep quality in the first 4 weeks of recovery is meaningfully associated with post-concussion QOL or depression symptomatology outcomes in children and adolescents.

The timing of KS-52 and CDI-2 measurements may partly explain this observation. Given that 95.4% and 89.2% of participants completed RTS and RTA protocols, respectively, most participants would have been clinically recovered and asymptomatic by the time that these outcomes were assessed (3 months following RTS and RTA protocol completion). Considering that concussion symptoms can negatively contribute to decreased physical activity, decreased participation in social activities, academic problems, isolation, and difficulty in numerous aspects of normal daily functioning daily functioning (Dematteo et al., 2014; Moran et al., 2012; Novak et al., 2016; Russell et al., 2019; Todd et al., 2018), resolution from concussion symptoms and general biological recovery from concussion may explain why QOL and depression symptomatology improved in participants. This is supported by findings in a systematic review that observed that psychological and behavioural issues tend to resolve around the time of clinical recovery from concussion (Emery et al., 2016).

While this study supports that sleep quality in the first 4 weeks is not strongly associated with recovery outcomes, this does not necessarily indicate that sleep is not an important factor. This study does not take into consideration the relative change in sleep parameters over time, nor resolution of sleep issues. Findings from unpublished data using the same study population support that several sleep quality parameters are adversely affected by concussion but show trajectories of improvement throughout 4 weeks of recovery (Fisher et al., Unpublished). Given the importance of sleep in the general maintenance of cognitive, physical, and mental health (Chaput et al., 2016) and evidence showing associations between poor sleep, symptoms exacerbation, (Blake et al., 2019; Hinds et al., 2016; Hoffman et al., 2017; Kostyun et al., 2015; Towns et al., 2015; Lavigne et al., 2015) and impaired cognitive performance (Sufrinko et al., 2015), a return to pre-injury sleep quality may also correspond with symptom improvement. Therefore, it is possible that recovery from concussion and improvements in QOL outcomes and depression symptomatology coincide with relative improvements in sleep quality or resolution of any existing sleep issues. However, more research is needed to appropriately examine this hypothesis.

Interestingly, the results of this study are inconsistent with findings from previous research. Results from Bramley et al., 2017 and Chung et al., 2019 support that children and adolescents with subjectively poor sleep quality experience significantly longer recovery durations. Other findings also indicate that poor subjective sleep quality is associated with increased anxiety and depression symptomatology in children and adolescents (Chung et al., 2019) and poorer QOL in young adults (Blake et al., 2019). Although, differences in the measurement techniques of sleep quality may account for the inconsistencies between the findings of current study and previous research. Other studies have demonstrated that objective and subjective sleep findings often differ (Zhang & Zhao, 2007), even after concussion (Allan et al., 2017; Berger et al., 2017). Thus, it is not surprising that recovery outcomes associated with subjective and objective measurement differ as well. This discrepancy appears to exemplify an important distinction in the relationship between objective and subjective sleep quality and their relationship with recovery outcomes. Given that subjective sleep quality, rather than objective sleep quality, appears to be associated with recovery outcomes, this may suggest that the way a person feels about the quality of their sleep is a more important predictor of recovery outcomes than how they slept objectively.

3.51 Limitations

The results of this study should be interpreted in consideration of inherent limitations. While multiple days of sleep information were used to develop sleep quality averages in order to limit the effects of day-to-day variation, inter-participant variability and inconsistency of available data required that sleep quality outcomes were measured in participants only throughout the first 4 weeks of recovery and were aggregated weekly, rather than continuously. This study cannot validly comment on the relationship between sleep quality and recovery outcomes beyond 4 weeks. Therefore, sleep quality was not assessed up until the point of recovery for several participants. Furthermore, a significant limitation of the current study is that daytime sleep behaviour was not incorporated into analyses. Given that daytime sleep activity has been shown to affect nighttime sleep behaviour and shift circadian rhythm cycles (Mosti et al., 2016), this study cannot validly comment on the relationship between all post-concussion sleep activity and recovery. Additionally, this study was unable to determine how relative changes in a person's sleep quality over time affect recovery outcomes. Perhaps, the association between relative changes in sleep quality over time may better predict recovery outcomes. Future studies should make greater attempts to explore the affects of objective sleep quality from the time of injury until, and beyond clinical recovery to more accurately determine if sleep quality at specific recovery time-points is associated with recovery outcomes.

3.52 Conclusions

Objective sleep parameters within the first 4 weeks of recovery were not associated with time to RTS or RTA, suggesting that post-concussion sleep quality is not predictive of concussion recovery length in children and adolescents. Furthermore, sleep parameters were not meaningfully correlated with post-concussion QOL or depression symptomology outcomes. Collectively, these results provide evidence to suggest that objective sleep quality after injury is not a significant determinant of post-concussion recovery outcomes.

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Table 1. Participant characteristics.

	Participant Sample (n = 65)
Age: mean (range)	12.6 (2.9)
Sex: n (%)	
Male	34 (52.3%)
Female	31 (47.7%
Number of Concussions: n (%)	
One	49 (75.4%)
Two or more	16 (24.6%)
Initial PCSS Score: med. (2nd, 3rd qrt)	30 (15, 52)
Mechanism of Injury: n (%)	49 (75.4%)
Sports	11 (16.9%)
Recreation (Non-Sport Related)	5 (7.7%)
Other	
Premorbid Conditions: n (%)	
Anxiety	7 (10.8%)
Depression	2 (3.1%)
Learning Disability	8 (12.3%)
Attention Deficit Hyperactivity Disorder	6 (9.2%)
Developmental Disorder	1 (1.5%)
Headaches	11 (21.5%)
Diagnosed Sleep Disorder	1 (1.5%)
Subjective Sleep Complaints: n (%)	
Preinjury Sleep Complaints	13 (20.0%)
Postinjury Sleep Complaints	31 (48.7%)
Return to School Protocol	
Completed: n (%):	62 (95.4%)
Did Not Complete: n (%):	3 (4.6%)
Time to RTS med.: (2nd, 3rd qrt):	50.0 (30.4, 61.5)
Return to Activity Protocol	
Completed: n (%)	58 (89.2%)
Did Not Complete: n (%)	7 (10.8%)
Time to RTA: med.: (2nd, 3rd qrt):	52.5 (35.6, 64.4)

PCSS = Post-Concussion Symptom Scale
RTS = Return to School
RTA = Return to Activity

Table 2. Results from univariate Cox proportional hazards models examining the association between weekly sleep parameters and time to RTS and time to RTA (n = 65).

		Time to RTS			Time to RTA		
Sleep parameter	**n**	**Hazards Ratio**	**95% CI**	**p-value**	**Hazards Ratio**	**95% CI**	**p-value**
Total Sleep Time (hours)							
Week 1	38	1.00	0.70, 1.43	0.994	1.00	0.71, 1.42	0.992
Week 2	51	1.10	0.80, 1.51	0.560	1.04	0.76, 1.44	0.791
Week 3	44	1.27	0.89, 1.81	0.195	1.27	0.86, 1.86	0.231
Week 4	32	1.34	0.86, 2.10	0.196	1.31	0.83, 2.06	0.246
Sleep Efficiency (%)							
Week 1	38	1.00	0.95, 1.06	0.900	0.99	0.93, 1.04	0.618
Week 2	51	0.99	0.94, 1.03	0.620	0.96	0.92, 1.01	0.137
Week 3	44	0.99	0.93, 1.05	0.768	0.97	0.91, 1.03	0.291
Week 4	32	1.07	0.98, 1.17	0.150	1.04	0.96, 1.14	0.324
Wake After Sleep Onset (minutes)							
Week 1	38	1.00	0.99, 1.01	0.358	1.00	0.99, 1.01	0.904
Week 2	51	1.00	0.99, 1.01	0.940	1.00	0.99, 1.01	0.344
Week 3	44	1.00	0.99, 1.01	0.608	1.00	0.99, 1.01	0.423
Week 4	32	0.99	0.98, 1.00	0.230	0.99	0.98, 1.01	0.309
Average Length of Arousal (minutes)							
Week 1	38	0.95	0.75, 1.21	0.698	0.97	0.79, 1.18	0.738
Week 2	51	1.11	0.82, 1.51	0.509	1.28	0.94, 1.75	0.123
Week 3	44	1.06	0.80, 1.40	0.699	1.14	0.85, 1.53	0.386
Week 4	32	0.69	0.47, 1.02	0.065	0.83	0.57, 1.20	0.319
Number of Arousals (n/ hour)							
Week 1	38	0.77	0.49, 1.20	0.243	0.86	0.55, 1.33	0.493
Week 2	51	0.84	0.57, 1.22	0.356	0.86	0.57, 1.29	0.458
Week 3	44	1.01	0.64, 1.59	0.978	0.91	0.56, 1.47	0.691
Week 4	32	0.88	0.55, 1.39	0.584	0.76	0.46, 1.25	0.283

Table 3. Summary table of median initial and final KS-52 T-Scores (n = 61) for physical and psychological wellbeing and Total CDI-2 T-Score (n=63). The median difference score between participants initial and final T-Scores is displayed.

Outcome Measure	Initial Assessment T-Score (Med.; 2nd, 3rd qrt)	Final Assessment T-Score (Med.; 2nd, 3rd qrt)	Difference Score (Med.; 2nd, 3rd qrt)
Kidscreen-52			
Physical Wellbeing	36.6 (30.6, 44.7)	49.6 (47.1, 59.4)	14.6 (8.2, 20.9)
Psychological Wellbeing	45.1 (36.9, 49.3)	54.5 (47.1, 68.5)	8.2 (0.0, 16.1)
Children's Depression Inventory-2			
Total Score	47.0 (43.0, 56.0)	43.0 (40.0, 46.0)	-4.0 (-10.0, 0.0)

Table 4. Spearman rank correlations between sleep parameters across 4-weeks post-injury and final assessment KS-52 T-Scores and KS-52 difference scores (n = 61).

		Final T-Score		Difference Score	
Sleep Parameter	**Obs.**	**Physical Wellbeing (rho)**	**Psychological Wellbeing (rho)**	**Physical Wellbeing (rho)**	**Psychological Wellbeing (rho)**
Total Sleep Time (hours)					
Week 1	33	-0.16	0.07	0.00	0.02
Week 2	47	-0.05	0.05	0.05	0.08
Week 3	40	0.02	0.08	0.05	0.08
Week 4	30	-0.09	0.04	0.00	0.14
Sleep Efficiency (%)					
Week 1	33	-0.11	-0.11	0.14	0.07
Week 2	47	-0.26	-0.22	-0.10	-0.14
Week 3	40	-0.40*	-0.34	-0.17	-0.16
Week 4	30	-0.19	-0.19	0.01	0.05
Wake After Sleep Onset (minutes)					
Week 1	33	0.03	0.25	-0.10	0.02
Week 2	47	0.14	0.17	0.07	0.08
Week 3	40	0.37	0.37	0.29	0.21
Week 4	30	-0.03	0.12	-0.07	0.03
Average Length of Arousal (minutes)					
Week 1	33	-0.14	-0.09	-0.20	-0.20
Week 2	47	0.19	0.13	0.12	0.04
Week 3	40	0.22	0.17	0.04	0.05
Week 4	30	0.19	0.17	-0.12	-0.12
Number of Arousals (n/ hour)					
Week 1	33	0.12	0.23	-0.06	0.15
Week 2	47	-0.04	0.08	0.01	0.03
Week 3	40	0.21	0.32	0.31	0.28
Week 4	30	-0.16	0.03	0.08	0.16

* = $p < 0.05$

Table 4. Spearman rank correlations between sleep parameters across 4-weeks post-injury and final assessment CDI-2 T-Scores and CDI-2 difference scores (n = 63).

Sleep Parameter	Obs.	Final T-Score (rho)	Difference Score (rho)
Total Sleep Time (hours)			
Week 1	35	-0.24	-0.15
Week 2	48	-0.17	-0.03
Week 3	41	-0.12	-0.01
Week 4	32	0.04	0.05
Sleep Efficiency (%)			
Week 1	35	-0.20	-0.43*
Week 2	48	0.01	-0.05
Week 3	41	0.10	0.04
Week 4	32	0.15	0.04
Wake After Sleep Onset (minutes)			
Week 1	35	0.08	0.38
Week 2	48	0.05	0.02
Week 3	41	0.05	-0.05
Week 4	32	-0.01	-0.09
Average Length of Arousal (minutes)			
Week 1	35	0.23	0.36
Week 2	48	0.14	0.24
Week 3	41	-0.02	0.13
Week 4	32	-0.16	0.09
Number of Arousals (n/ hour)			
Week 1	35	0.07	0.10
Week 2	48	-0.02	-0.24
Week 3	41	-0.05	-0.18
Week 4	32	0.08	-0.23

* = $p < 0.05$

3.7 Appendix

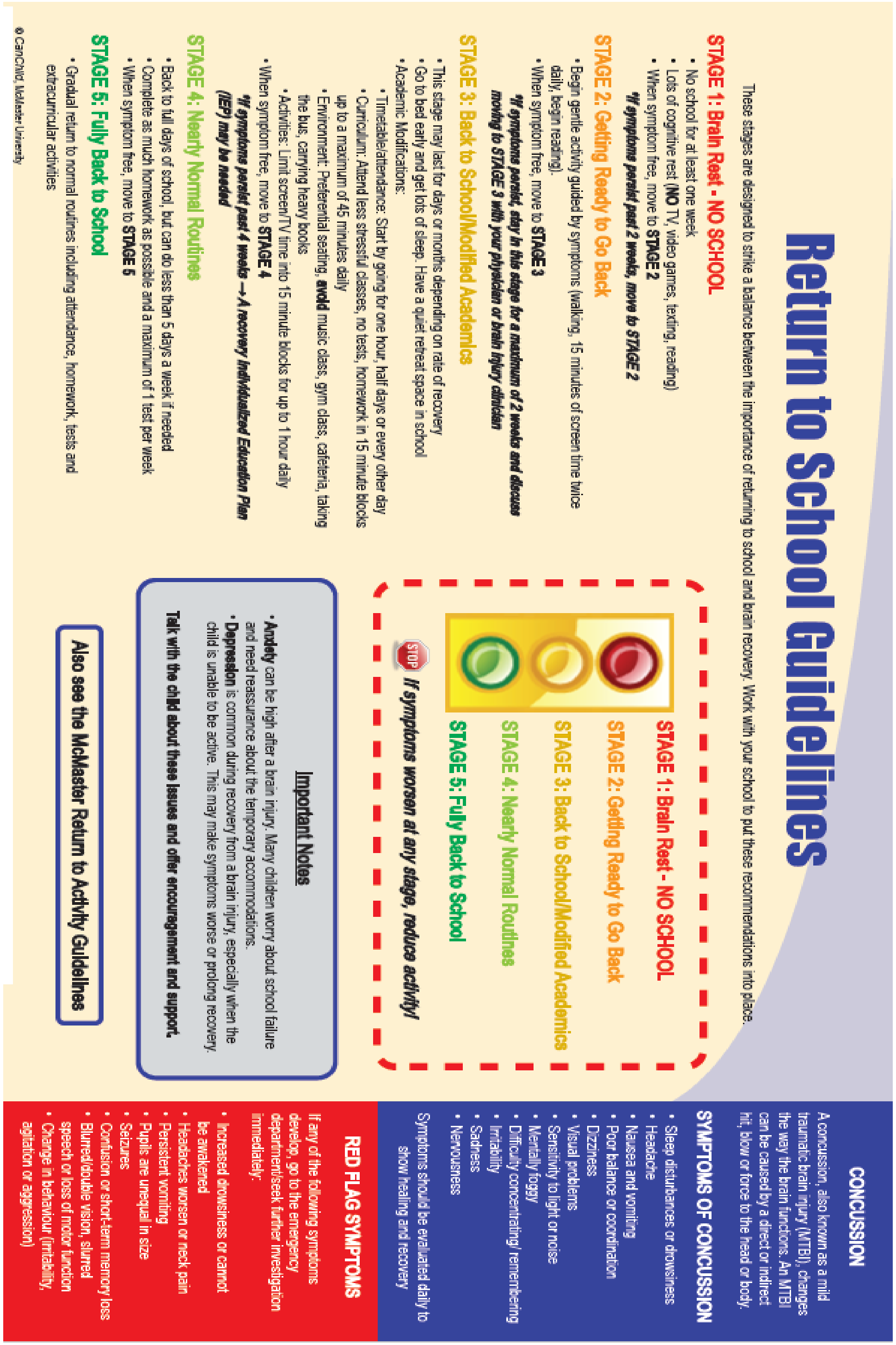
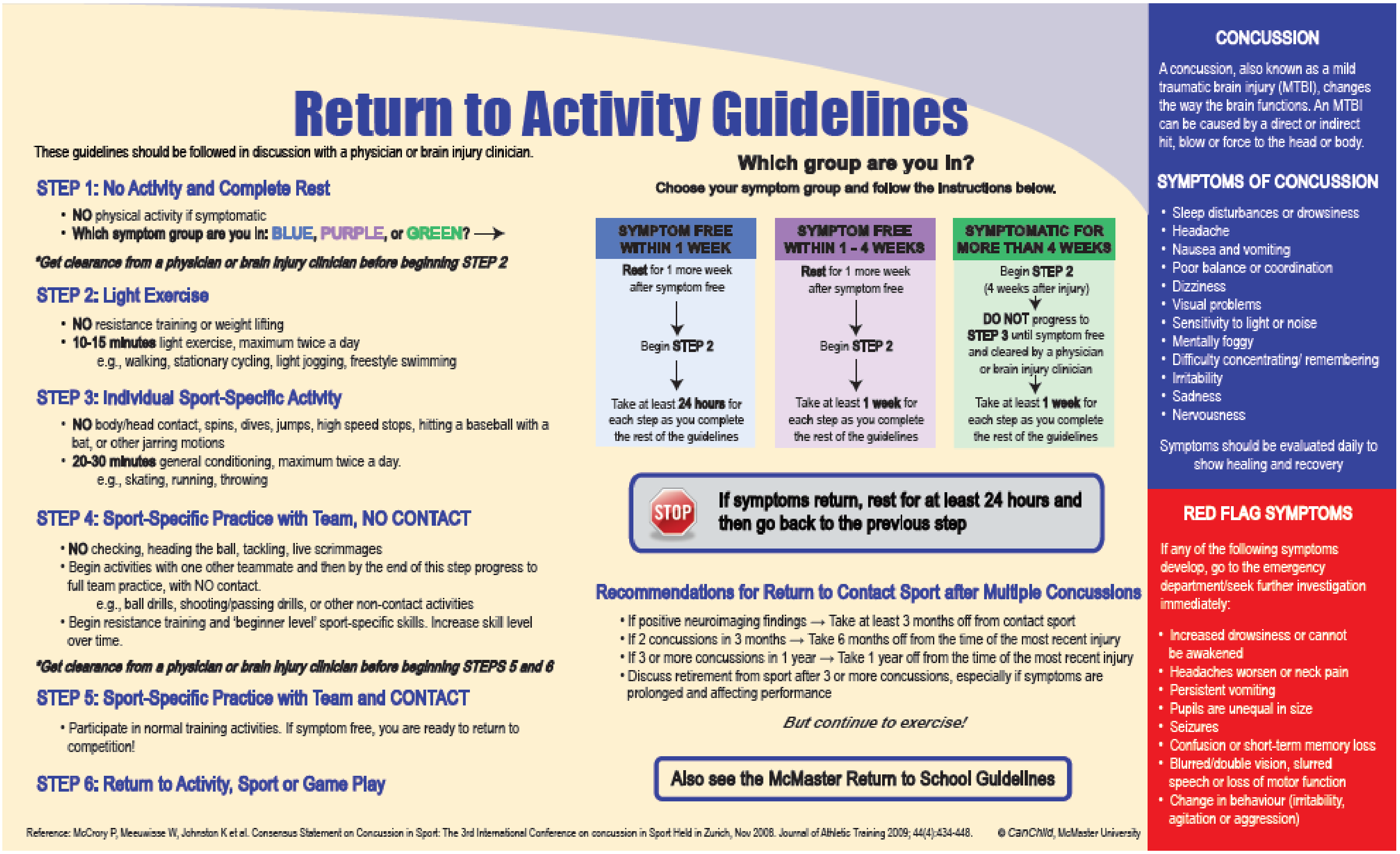


Figure A1. Return to School guidelines followed by participants.



Return to Activity Guidelines

These guidelines should be followed in discussion with a physician or brain injury clinician.

STEP 1: No Activity and Complete Rest

- **NO** physical activity if symptomatic
- **Which symptom group are you in: BLUE, PURPLE, or GREEN?** →

Get clearance from a physician or brain injury clinician before beginning STEP 2

STEP 2: Light Exercise

- **NO** resistance training or weight lifting
- **10-15 minutes** light exercise, maximum twice a day
  e.g., walking, stationary cycling, light jogging, freestyle swimming

STEP 3: Individual Sport-Specific Activity

- **NO** body/head contact, spins, dives, jumps, high speed stops, hitting a baseball with a bat, or other jarring motions
- **20-30 minutes** general conditioning, maximum twice a day.
  e.g., skating, running, throwing

STEP 4: Sport-Specific Practice with Team, NO CONTACT

- **NO** checking, heading the ball, tackling, live scrimmages
- Begin activities with one other teammate and then by the end of this step progress to full team practice, with NO contact.
  e.g., ball drills, shooting/passing drills, or other non-contact activities
- Begin resistance training and 'beginner level' sport-specific skills. Increase skill level over time.

Get clearance from a physician or brain injury clinician before beginning STEPS 5 and 6

STEP 5: Sport-Specific Practice with Team and CONTACT

- Participate in normal training activities. If symptom free, you are ready to return to competition!

STEP 6: Return to Activity, Sport or Game Play

Which group are you in?

Choose your symptom group and follow the instructions below.

SYMPTOM FREE WITHIN 1 WEEK	SYMPTOM FREE WITHIN 1 - 4 WEEKS	SYMPTOMATIC FOR MORE THAN 4 WEEKS
Rest for 1 more week after symptom free	**Rest** for 1 more week after symptom free	Begin **STEP 2** (4 weeks after injury)
↓ Begin **STEP 2**	↓ Begin **STEP 2**	↓ **DO NOT** progress to **STEP 3** until symptom free and cleared by a physician or brain injury clinician
↓ Take at least **24 hours** for each step as you complete the rest of the guidelines	↓ Take at least **1 week** for each step as you complete the rest of the guidelines	↓ Take at least **1 week** for each step as you complete the rest of the guidelines

STOP **If symptoms return, rest for at least 24 hours and then go back to the previous step**

Recommendations for Return to Contact Sport after Multiple Concussions

- If positive neuroimaging findings → Take at least 3 months off from contact sport
- If 2 concussions in 3 months → Take 6 months off from the time of the most recent injury
- If 3 or more concussions in 1 year → Take 1 year off from the time of the most recent injury
- Discuss retirement from sport after 3 or more concussions, especially if symptoms are prolonged and affecting performance

But continue to exercise!

Also see the McMaster Return to School Guidelines

CONCUSSION

A concussion, also known as a mild traumatic brain injury (MTBI), changes the way the brain functions. An MTBI can be caused by a direct or indirect hit, blow or force to the head or body.

SYMPTOMS OF CONCUSSION

- Sleep disturbances or drowsiness
- Headache
- Nausea and vomiting
- Poor balance or coordination
- Dizziness
- Visual problems
- Sensitivity to light or noise
- Mentally foggy
- Difficulty concentrating/ remembering
- Irritability
- Sadness
- Nervousness

Symptoms should be evaluated daily to show healing and recovery

RED FLAG SYMPTOMS

If any of the following symptoms develop, go to the emergency department/seek further investigation immediately:

- Increased drowsiness or cannot be awakened
- Headaches worsen or neck pain
- Persistent vomiting
- Pupils are unequal in size
- Seizures
- Confusion or short-term memory loss
- Blurred/double vision, slurred speech or loss of motor function
- Change in behaviour (irritability, agitation or aggression)

Reference: McCrory P, Meeuwisse W, Johnston K et al. Consensus Statement on Concussion in Sport: The 3rd International Conference on concussion in Sport Held in Zurich, Nov 2008. Journal of Athletic Training 2009; 44(4):434-448. © CanChild, McMaster University

Figure A2. Return to Activity guidelines followed by participants.

CHAPTER FOUR:
DISCUSSION OF RESULTS

It is well established that proper sleeping behaviour is essential for the maintenance of health and for optimal function. Yet, sleep quality following concussion remains understudied, particularly in pediatric populations. Sleep quality was assessed for 4 weeks post-concussion to explore the effects of concussion and concussion recovery in the context of objectively measured sleep quality. The decision to examine 4 weeks of post-concussion sleep was both theory and data driven, allowing me to: 1) capture information about sleep parameters from the early phases of injury until the expected concussion recovery time in children and adolescents (McCrory et al., 2017); 2) ensure that sleep information used in analyses was from participants who were recruited soon after their concussion (within 28 days); and 3) allow a relatively equal distribution of sleep data for each week being analysed. The results of Study One (Chapter 2) provide novel information that investigate how objective sleep quality is longitudinally affected by concussion and explores if sleep quality changes are predicted by time-related, demographic, premorbid, or injury-related factors. Study Two (Chapter 3) expands upon the findings of Study One, exploring if changes seen in post-concussion sleep quality are related to recovery outcomes. Together, these studies answer how concussion affects sleep and in turn, how that impacts recovery from concussion. This discussion will review and integrate the results of these studies in the context of current literature, theory, clinical implications of this research and will recommend new research directions.

4.1 Study One

In the first study, the trends of five objective sleep quality parameters of children and adolescents were evaluated using actigraphy and described throughout the first weeks of recovery. Results revealed that the sleep quality of concussed participants appears to be significantly impacted by concussion relative to healthy children and adolescents. When compared with published normal sleep estimates (B. C. Galland et al., 2018), both child and adolescent participants were found to have significantly poorer sleep efficiency (SE) and wake after sleep onset (WASO) across all 4 weeks of recovery. Participant WASO duration appeared to be most noticeably impacted. This implies that youth recovering from concussion experience greater periods of arousal throughout the night. Clinically, increased periods of arousal may suggest that there are alterations in sleep regulation that lead to interrupted sleep (Shrivastava et al., 2014). Therefore, participants may be spending less time in the later, deep stages of sleep. In the context of the theory of restorative sleep (Adam, 1980), mentioned in Chapter One, this would mean that children and adolescents with concussion are receiving less restorative sleep than the normal population. Theoretically, this may account for some of the fatigue-based, cognitive, and mental symptoms experienced after concussion.

In the context of previous research, these results appear to disagree with findings which observed no differences in objective sleep parameters between concussed and healthy participants when examined using polysomnography (PSG) (Gosselin et al., 2009a) and actigraphy (Allan et al., 2017; Raikes & Schaefer, 2016). However, a few important differences may explain the discrepancies between this study and others. Firstly, the age of the study population in these studies included young and older adults. Given that sleep behaviour differs between youth and adult populations (Li et al., 2018; Ohayon et al., 2004), it may also be true that sleep is affected by concussion differently for different age groups. Secondly, these studies took fewer nights of sleep data into consideration. Given the significant night-to-night variation observed in participants sleep data and the small population size used in other studies, it may be difficult to observe significant differences in concussed participants if fewer nights of data and fewer participants were used. A strength of this study is that it uses several nights of data and a larger sample size to assess changes in sleep quality. Although, conclusions from this study are limited given that a control cohort was not available for comparison. The addition of a healthy control group or a group with non-concussive injury would greatly increase the validity of claims presented in Study One.

Trend analysis of total sleep time (TST) revealed that sleep quantity trends did not follow expected trajectories. In both children and adolescent participants, median TST increased from week 1 to week 3, followed by a slight decrease in week 4. However, other studies examining young adults and adults have found that there is a consistent acute increase in TST followed by a decline throughout the first month (Chiu et al., 2013; Raikes & Schaefer, 2016). The discrepancies between Study One and these other studies may be again be related to the ages of the populations studied, resulting in different sleep quality trajectories following concussion. Another important note is that several participants did not have sleep data within the first week of recovery. Therefore, the population size was limited during the acute phase of recovery and resulted in a substantial amount of variance in TST. As a result, the estimates of TST during the acute 7-day phase may not be as accurate as TST estimates in the following weeks of recovery.

When sleep quality trajectories were examined, several sleep parameters showed signs of improvement, particularly in children. While sleep parameters still significantly differed from normal values after 4 weeks, most sleep parameter outcomes in weeks 3 and 4 more closely resembled normal sleep data estimates published by Galland et al., 2018. In fact, SE was found to significantly improve with time since injury. With consideration to Study Two, most participants had not yet completed RTS or RTA protocols by week 4 (89.9% and 86.5%, respectively) and were still recovering from their concussion. Given the trajectory of sleep parameters observed, it is likely that sleep quality continues to improve through the remainder of the participants recovery. As sleep quality improves, theoretically, participants will receive more restorative sleep, thereby promoting processes that facilitate recovery. Therefore, sleep may be an important determinant of recovery length and post-concussion outcomes.

This study also indicates that demographic factors are an important consideration in sleep quality after concussion. Mixed effects analysis revealed that older age (from ages 5 to 18) was significantly associated with decreased total sleep time (TST). This is consistent with previous literature that has found a decrease in TST from childhood to adolescents (Galland et al., 2018; Maslowsky & Ozer, 2014; Williams et al., 2013). Analyses also revealed that female sex was significantly associated with longer WASO and average arousal length (AAL), and was strongly associated with poorer SE. This suggests that females may be more likely to experience poor sleep quality following a concussion. Perhaps this, in the context of the theory of restorative sleep, may partially explain why females often require longer to recover from concussion**.** Other strong predictors of concussion recovery, such as history of concussions and initial symptom score (Iverson et al., 2017; Marshall et al., 2019b; Zemek, Barrowman, Freedman, Gravel, Gagnon, McGahern, Aglipay, Sangha, Boutis, Beer, Craig, Burns, Farion, Mikrogianakis, Barlow, Dubrovsky, Meeuwisse, Gioia, Meehan, Beauchamp, Kamil, Grool, Hoshizaki, Anderson, Brooks, Yeates, Vassilyadi, Klassen, Keightley, Richer, De Matteo, et al., 2016) were not associated with sleep quality outcomes. Therefore, age and sex appear to be important predictors of post-concussion sleep quality and quality in children and adolescents, respectively.

Interestingly, mixed effects analysis revealed that that preinjury and post-injury sleep complaints were not found to be significant predictors of any sleep quality outcomes. Given this, and previous literature supporting a discrepancy between subjective and objective sleep outcomes (Allan et al., 2017; Berger et al., 2017; Gosselin et al., 2009), this study provides further reason that objective and subjective sleep quality need to both be considered following a concussion. Future research and clinical practice should consider both subjective and objective sleep quality as part of the sleep phenomena.

These results provide evidence that: 1) sleep quality is affected after concussion; 2) sleep quality shows improvement throughout recovery; and 3) age and sex are associated with sleep quality outcomes, older age and female sex have more impact on sleep quality. However, consideration must be made to the limitations of this study. For instance, only 4 weeks of sleep data were examined which did not capture the amount of time required for sleep quality parameters to return to normal. Furthermore, premorbid sleep patterns were not available, thus, "normal" sleep estimates could not be determined for the specific study population. Consequentially, this study cannot validly determine whether participants did or did not return to their normal sleep quality, nor can this study determine if the sleep outcomes observed were due to biological concussion effect or secondary effects such as anxiety. Additionally, analyses did not consider the effects of daytime activity. Given that daytime sleep habits are commonly altered after concussion (Ponsford et al., 2013; Wiseman-Hakes et al., 2019), the daytime sleep and physical activity may influence nighttime sleep outcomes.

Future studies should attempt to monitor sleep quality before injury if possible or include a matched control group to better establish normal sleep quality estimates. Sleep quality should also be monitored up to and beyond recovery to determine if and when sleep quality returns back to a normal state. It may also be interesting to determine if there are differences in the sleep quality trajectories of persons who recover quickly, as expected, and more slowly. Future studies should also examine objective sleep outcomes with consideration to the effect of daytime activity.

4.2 Study Two

The second study evaluated if objective post-concussion sleep quality was associated with recovery outcomes. Specifically, this study examined the association between weekly sleep parameter outcomes and the time to complete return to school (RTS) and return to activity (RTA) protocols. Additionally, the relationship between sleep parameters and quality of life (QOL) and depression symptomatology were assessed using the Kidscreen 52 (KS-52) (Ravens-Sieberer et al., 2005b) and the Children's Depression Inventory 2nd Edition (CDI-2; Kovacs, 2011), respectively. Given previous research demonstrating an association between subjective sleep quality and recovery length (Bramley et al., 2017; Chung et al., 2019; Hinds et al., 2016; Hoffman et al., 2019) and using the theory of restorative sleep to inform rationale, it was hypothesized that a greater TST and SE would contribute to quicker recovery times and better QOL and depression symptomatology outcomes. Conversely, it was hypothesized that a greater number of arousals (NOA) and longer WASO and average arousal length (AAL) would result in slower recovery and worse QOL and depression symptomatology outcomes.

However, this was not found to be the case. Sleep quality parameters, across all 4 weeks, were not significantly associated with time to RTS or RTA. These results appear to suggest that objective sleep quality is not associated with recovery duration. Although, given the import role sleep plays in restorative processes, it is unlikely that objective sleep quality does not play any role in the recovery process. But, this role may be overshadowed by more important factors associated with recovery. Established recovery factors such as age, sex, concussion history, premorbid conditions, and initial symptom presentation (Iverson et al., 2017; Marshall et al., 2019b; Zemek, Barrowman, Freedman, Gravel, Gagnon, McGahern, Aglipay, Sangha, Boutis, Beer, Craig, Burns, Farion, Mikrogianakis, Barlow, Dubrovsky, Meeuwisse, Gioia, Meehan, Beauchamp, Kamil, Grool, Hoshizaki, Anderson, Brooks, Yeates, Vassilyadi, Klassen, Keightley, Richer, De Matteo, et al., 2016) may influence recovery duration more than sleep quality.

The results of this study are similar to those found in a prospective cohort study of 423 collegiate athletes by Hoffman et al., 2017, who compared the recovery length of post-concussion sleep duration groups during the acute phase of concussion. Hoffman et al., 2017 found that the number of days to asymptomatic did not significantly differ between persons who slept more than, less than, or the same amount as they did before they experienced a concussion. These observations are consistent with results from Study Two, which demonstrated that TST was not significantly predictive of time to RTS or RTA.

Yet, in a later study by Hoffman et al., 2019, examining other sleep quality parameters, researchers identified a moderate positive correlation between WASO and days to asymptomatic and a negative correlation between SE and days to asymptomatic. This would suggest that objective post-concussion sleep quality does play a more direct role than what was found in Study Two. However, a few important differences and limitations in Hoffman et al., 2019 study may explain some of the discrepancies in results. Firstly, the population ages of these studies differed. Given evidence that recovery timelines for children and adults are different (McCrory et al., 2017), factors associated with recovery may also differ. Secondly, the population size (n = 14) examined by Hoffman et al., 2019 was substantially smaller, limiting the strength of any results observed. Lastly, Hoffman et al., 2019 used a correlational analysis to examine the relationship between sleep quality and recovery, whereas Study Two implemented Cox proportional hazards models. The statistical methodology implemented in Study Two (i.e. survival analysis) is stronger analysis technique than correlation analysis used by Hoffman et al., 2019. As opposed to correlation analysis, which only shows the relationship between two variables, survival analysis demonstrates the effects of one variable on another and incorporates the information of participants who did not reach recovery. This allowed us to determine how recovery length is affected by sleep parameters with a larger sample size, thus increasing the power of the study to detect the association if it exists. Therefore, the results drawn from Study Two are likely more robust and more clinically relevant to a pediatric population.

Increases in both physical and psychological wellbeing KS-52 T-Scores and decreases CDI-2 Total T-Scores were observed from initial to final assessment. These outcomes indicate that participants experienced improvements in their QOL and in their post-concussion depression symptomatology. Further analysis into recovery outcomes revealed that sleep quality parameters were not strongly correlated with final KS-52 or CDI-2 outcomes, nor were they meaningfully correlated with changes in KS-52 or CDI-2 scores from initial to final assessment. Some significant correlations between SE, QOL, and depression symptomatology outcomes were found. Week 3 and week 1 SE were moderately correlated with poorer physical wellbeing outcomes and decreases in depression symptomatology, respectively. Yet, given the small magnitude of the correlations, and no further evidence of any other trends, it is likely that these findings are not clinically meaningful. Thus, these results appear to suggest that sleep quality is not associated with post-concussion QOL and depression symptomatology outcomes.

While sleep quality was not associated with these outcomes, there are a few possible explanations for this observation. Given that nearly all participants completed RTS and RTA protocols (95.4% and 89.2%, respectively) and KS-52 and CDI-2 outcomes were measured 3 months post-protocol completion, participant outcomes were assessed mostly in recovered, asymptomatic participants. Given that symptom burden can contribute to poor QOL and mental health (Dematteo et al., 2014; Moran et al., 2012; Novak et al., 2016; Russell et al., 2019; Todd et al., 2018), biological recovery and symptom resolution may explain why improvements to both QOL and depression symptomatology were observed. This explanation is consistent with a the findings of a systematic review which observed that post-concussion psychological and behavioural issues often resolve around the time of recovery (Emery et al., 2016).

It is important to note that these results do not completely rule out that sleep quality has no role in recovery. Rather, they only indicate that individual sleep parameters in the first 4 weeks are not associated with recovery outcomes. This study does not take into consideration the relative change in sleep parameters over time, nor resolution of sleep issues. With respect to findings from Study One, affected sleep parameters trended towards improvement. Considering that post-concussion sleep issues have been associated with symptom exacerbation (Blake et al., 2019; Hinds et al., 2016; Hoffman et al., 2017; Kostyun et al., 2015; Towns et al., 2015; Lavigne et al., 2015), resolution of these sleep issues may relate to symptom recovery. Therefore, it may be true that improvements in sleep quality throughout recovery or resolution of sleep issues coincide with RTS or RTA completion as well as improvements in participant recovery outcomes. It may also be true that any acute post-concussion sleep quality issues that may have been present would likely have disappeared by the time QOL and depression symptomatology outcomes were measured. However, this study cannot confirm this hypothesis. Future studies should examine if changes in sleep quality and daytime wakefulness are associated with changes in QOL or depression symptomatology.

While the results of Study One indicate that sleep quality is affected by concussion, these results demonstrate that changes to post-concussion sleep quality are not directly associated with time to recovery, QOL and depression symptomatology. However, this study must also be considered in light of its limitations. Mainly, although sleep was measured daily, the variability and consistency of available data required that sleep quality outcomes were aggregated weekly rather than continuously. Consequently, analyses did not account for relative changes in a sleep quality over time. Furthermore, sleep parameters were not analysed up the point of recovery in participants. Thus, sleep quality in the later stages of recovery was not accounted for and important information regarding the relationship between sleep quality and recovery outcomes at these later times may have been missed. Future studies should measure sleep quality from injury until recovery and assess if changes in sleep quality over time are associated with recovery outcomes. Additionally, RTS and RTA was used as a measurement of recovery, theoretically this should also indicate symptomatic resolution but this was not always the case. This was exemplified in a study by (DeMatteo et al.,2019), where 21% and 15% of children were still symptomatic at the time of RTS and RTA protocol completion, respectively. Thus, participants who had completed RTS and RTA protocols may still have been symptomatic when they had been deemed recovered. This could lead to a bias of shorter recovery time in participants, leading to misleading associations between sleep quality and recovery duration. Given the association between sleep issues and the exacerbation of pain and concussion symptom presentation (Blake et al., 2019; Hinds et al., 2016; Hoffman et al., 2017; Kostyun et al., 2015; Towns et al., 2015; Lavigne et al., 2015), perhaps the association between objective sleep quality outcomes and time to symptom resolution may yield different results.

4.3 Integrating the Results of Studies

These studies describe the relationships of concussion to sleep quality and of sleep quality to recovery. Study One demonstrated that sleep quality is affected by concussion. Participants had significant increases in the amount of time spent awake at night and poorer SE. As discussed previously, under the theory of restorative sleep, we would hypothesise that participants with poorer sleep quality outcomes would experience poorer recovery outcomes. However, Study Two provided evidence that objective sleep quality within the first 4 weeks of recovery is not associated with time to RTS and RTA, QOL, and depression symptomatology, as hypothesized. Yet, this does not necessarily mean this theory is completely wrong. There is enough evidence that sleep still contributes to restorative function, thus it is likely that sleep does play some role relating to concussion-specific outcomes. Findings from Study One, support that sleep quality improves throughout recovery. It is possible that these improvements coincide with, or contribute to recovery outcomes. More research should be devoted to uncovering what impact relative changes in sleep quality may have following pediatric concussion.

4.4 Clinical Implications

The most recent consensus on concussion prescribes acute rest during the days following a concussion, stating that physical and cognitive rest may ease symptom severity and promote recovery (McCrory et al., 2017). Yet, rest and sleep guidelines provided by concussion management protocols remain unclear and un-specific, often resulting in poor consideration to sleep outcomes in a clinical setting (Mosti et al., 2016). This is likely a reflection of limited post-concussion sleep research evaluating how sleep affects recovery, the efficacy of sleep interventions in persons with concussion, and how those interventions affect recovery. Furthermore, there has been little consideration as to how sleep should be assessed longitudinally and what steps can be taken to mitigate sleep issues.

While the results from these studies may not have indicated that sleep quality is directly associated with recovery outcomes, they do suggest that youth with concussion experience issues with their sleep, particularly in females. This information should be used to inform and update our current understanding of post-concussion sleep disturbances (SD). As discussed in Chapter One, issues with sleep quality can be detrimental for an individual and still likely has some role in recovery from concussion. Therefore, with consideration to the results of Study One, greater efforts should be made to monitor objective sleep quality of children and adolescents following a concussion. Additionally, clinicians should understand and distinguish between measuring sleep subjectively and objectively in persons with concussion.

However, because sleep quality appears to change throughout recovery and vary day-to-day, it is recommended that sleep should be measured at regular intervals (Mosti et al., 2016). This does present some considerable resource and practicality problems. Mainly, objective sleep measurement is relatively costly and requires a considerable amount of time and effort to extract and interpret several nights worth of sleep information. This would make continuous monitoring of objective sleep quality difficult and potentially unfeasible in all children with concussion. Furthermore, considering that subjective and objective sleep quality do not strongly correlate (Allan et al., 2017; Berger et al., 2017b; Gosselin et al., 2009a), it may be difficult to identify persons with objective sleep issues without first monitoring the objective sleep quality of everyone. These issues do present several challenges for attempting to implement sleep-specific concussion guidelines.

Yet, this thesis does seem to suggest that there a need for clinical interventions that mitigate post-concussion SD. While few concussion-specific sleep interventions studies have been conducted, some cognitive behavioural therapy interventions for insomnia (CBT-I) may be efficacious in alleviating post-TBI SDs. CBT-I acts to educate persons on their own sleep patterns and habits while tracking their sleep activity, setting sleep goals using video presentations and interactive tasks. BCT-I shows superior longer-term symptom reduction when compared with pharmacotherapy and is considered to be the first-line treatment for sleep impairments (Mitchell et al., 2012). In fact, two studies have found that CBT-I was a feasible means improving subjective sleep quality in adults with TBI (Theadom et al., 2018; Vincent & Lewycky, 2009). However, general attempts at improving sleep hygiene in children and adolescents such as, turning off cell phones, avoiding stimulants and keeping to a routine, may be an important first step in managing sleep issues.

Alternatively, melatonin supplementation may offer a cheaper and less time-consuming fix to post-concussion SD. A randomized double-blind placebo-controlled crossover study of adults with TBI found that melatonin supplementation significantly improved PSQI scores, increased SE on actigraphy, improved mental health, on the SF-36 v1 questionnaire, and reduced anxiety on the Hospital Anxiety Depression scale (Grima et al., 2018)**.** In youth, a retrospective chart review of 51 adolescents with persistent concussion symptoms found that melatonin supplementation improved the sleep of 67% of patients. Although, only self-reported difficulties falling and stay asleep were assessed, SD severity was not. Other researchers believe that melatonin may help with other common symptoms of concussion (Kuczynski et al., 2013; Rios et al., 2010). However, there is always a concern when providing medication to persons with concussion. Clinicians should be advised that there is a possibility that medications may exacerbate or mask symptoms which makes the assessment of recovery more difficult. Furthermore, it is unknown how melatonin supplementation affects the brain chemistry of developing injured children.

More research is required before sleep-specific recommendations or interventions are implemented into concussion management strategies. Although, given that the role of sleep and recovery is still poorly understood, efforts and management recommendations should be made to accommodate and encourage the recovery of persons with well researched risk-factors.

4.5 Conclusion

The goal of this research was to provide novel information regarding the effects of pediatric concussion on sleep quality and how sleep quality affects recovery in children and adolescents. Evidence from Study One confirms that objective sleep quality is altered after concussion, especially in females. This is the first known study to longitudinally describe how objective sleep quality changes over time, providing evidence that several sleep parameters are affected but show some signs of improvement throughout recovery. Additionally, observations from Study One add to a growing body of literature that finds discrepancies between objective and subjective measures of sleep quality. Study Two is the first known study to describe the relationship between sleep quality and recovery outcomes in youth. Finding support that objective sleep quality is not directly associated with time to RTS and time to RTA, nor is it strongly correlated with QOL or depression symptomology outcomes. This research provides novel information that furthers our understanding of how concussion affects the sleep quality of youth and what impact sleep quality has in relation to recovery. Findings from this thesis support that objective sleep quality should be evaluated in a clinical setting if sleep difficulties are disclosed, however, there is not enough supporting evidence that would suggest that objective sleep quality should be considered a modifiable target that promotes a faster recovery. More research is needed before sleep-specific recommendations are implemented into management strategies, future exploration into the role of objective sleep quality may lead to better management guidelines that more comprehensively support and promote the recovery of children and adolescents with concussion.

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