CAUTIOUS GAIT BEHAVIOUR: THE RELATIONSHIP BETWEEN GAIT AND COGNITION IN COMMUNITY-DWELLING ADULTS WITH CONCUSSION

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Abstract

Concussions can cause changes in gait and cognition. However, the relationship between these two areas has yet to be investigated in community-dwelling adults with concussion. The purpose of this thesis is to investigate the relationship between gait and cognition by characterizing cautious gait behaviour in individuals with concussion. Results from Chapter 2 revealed higher cautious gait behaviour in the Concussion Group than the Healthy Group. Cautious gait behaviour, characterized by higher double support time and lower cadence, was associated with worse symptom severity and cognitive function. Chapter 3 identified responsiveness and MDC_{95} values for different gait measures and revealed that recovery of cautious gait behaviour did not occur in more than half of the participants 12 weeks post-concussion. These findings suggest the use of cautious gait behaviour as a marker of subtle gait and cognitive impairments that can be used for the assessment and management of concussion.

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Chapter 1: Introduction

For many people, safe and effective gait is important for everyday functioning. Despite gait being a marker of overall health, there is a lack of understanding with regards to how gait is affected after concussion in community-dwelling adults. Concussions can result in changes in gait that, while perhaps being subtle, can pose challenges to safety. More specifically, concussion can either directly impact motor patterns that comprise gait or can have an indirect effect by impacting the cognitive processes that are necessary for effective gait. Impairments to cognitive processes like attention can occur after concussion, which ultimately lead to overly cautious gait behaviour. This, in turn, can affect the ability to carry out everyday tasks effectively and safely. By exploring the gait and cognitive deficits that occur after concussion and by relating these changes to the adoption of cautious gait behaviour in this understudied population, management and treatment of gait deficits in community dwelling adults with concussion can be improved.

This thesis is comprised of 4 chapters. In Chapter 1, a literature review of gait and cognition and their relationship in concussion is presented. In addition, I present a conceptual model that establishes the potential relationship between these areas and which also identifies the gaps in current knowledge. The studies that were completed to meet the purpose of this thesis are presented in Chapters 2 and 3. Chapter 2 aimed to investigate the acute effects of concussion on the relationship between gait and cognition, while the goal of Chapter 3 was to characterize recovery of cautious gait behaviour. Finally, Chapter 4 presents a general discussion of the findings of the whole thesis and identifies future directions for this work and provides an updated conceptual model.

1.1 Literature review

Concussion is a mild traumatic brain injury that is induced by biomechanical forces to the head (Mccrory et al., 2017). In Ontario, the mean incidence of concussion is 1153 per 100 000 residents in a year, with the majority of these injuries occurring in community-dwelling adults (Langer et al., 2020). Typically, concussions do not result in abnormal structural imagining, but rather result in brain disturbances via neurometabolic dysfunction (Bailes et al., 2013). This in turn results in a variety of symptoms that can be used to diagnose the injury. The cause of functional deficits in concussion is widely studied. Neuronal injury, altered brainstem-evoked potentials and brainstem dysfunction, dysregulation of neurotransmitters, and lower cerebral blood flow are all possible causes of deficits (Pavlova et al., 2018).

Concussion can cause a wide variety of symptoms such as physical and sensory symptoms, changes in emotional state, and changes in cognition (Bloom & Caron, 2019). Changes in gait and cognition are common post-injury and may impair day-to-day functioning. These changes are observed in a variety of populations such as young adults and athletes, but investigations of these changes are limited in community-dwelling adults. While studies in athletes are critical for informing safe return to play, understanding the impact of concussion in community-dwelling adults is crucial for making informed decisions about return to life decisions, as the consequences of concussion may impact activities such as work, school, and other everyday tasks. It is imperative to study the effects of concussions in non-athlete individuals as concussions more frequently occur by mechanisms other than sports related injuries (Public Health Agency of Canada, 2020). Additionally, community-dwelling adults may have different levels of education, fitness, and cognitive functioning than athletes, which may result in different impacts of concussion with regards to symptom severity, cognition and gait and the subsequent injury recovery (Allen, 2019; Clare et al., 2017; Greene et al., 2019).

For many individuals, gait is an essential everyday task that is required for interacting with our environment. The ability to walk safely is important to maintain quality of life and functional independence. Gait is a complex task that involves a cognitive load and is a predictor of a wide variety of health issues such as cognitive impairment and neurodegenerative diseases (Giladi et al., 2013). Injuries that affect gait may lead to a decreased quality of life and difficulty engaging in everyday tasks in a safe manner; therefore, it is important to understand how and the extent to which gait is impacted by concussion and how potential cognitive changes resulting from this injury are related to gait.

1.1.1 Symptoms

Concussion can result in a wide array of symptoms. Generally, these symptoms are classed across four different domains: cognitive, emotional, physical, and sleep/fatigue (Harmon et al., 2013). Symptoms can affect an individual's cognitive functioning as well as their ability to accurately complete neuropsychological assessments. Somatic symptoms such as nausea and sleep problems may impact focus and therefore performance on a test (Calvillo &

Irimia, 2020). In baseline testing of athletes, poor sleep quality the night before baseline cognitive testing was related to not only more symptoms, but also lower scores on cognitive assessments (McClure et al., 2014; Mihalik et al., 2013). This relationship is similarly observed in individuals with concussion, where poor sleep quality (sleeping too little, or too much) was related to worse Immediate Post-Concussion Assessment and Cognitive Test (ImPACT) scores in adolescent athletes (Kostyun et al., 2015). Post-traumatic headaches, for example, have been associated with impairments in reaction time and memory within the first week of injury (Kontos et al., 2013). Symptoms that are commonly reported by concussion patients such as mood, fatigue, and changes in sleep can affect performance on tests. For example, the Psychomotor Vigilance Task was used to assess sustained attention in patients with concussion; however, performance on this task was affected by sleep quality and fatigue (Sinclair et al., 2013). While the relationship between these symptoms and cognitive deficits is not fully understood, symptoms may cause a difficulty in sustaining attention, thereby impacting other cognitive functions (Kontos et al., 2016).

Concussion symptoms can also impact gait. For example, prolonged symptom duration has been associated with greater gait impairments such as a decrease in walking speed and cadence (Howell et al., 2017). Symptoms such as dizziness and balance problems can also affect gait. In a study by Hunt et al., participants with moderate/severe dizziness after concussion were found to have lower cadence (Hunt et al., 2021). Dizziness after concussion has also been associated with slower single and dual-task tandem gait (Smulligan et al., 2021). Changes in balance after concussion have been widely studied, and common changes such as increased sway can lead to poor postural stability during gait (Wood et al., 2019).

Despite the common use of symptom assessment in the diagnosis and treatment of concussion, self-reporting of symptoms has limitations that affect its usefulness. Subjective symptom reporting can be influenced by factors such as sleep, exercise, and psychosocial factors and therefore is not specific to concussion (Howell et al., 2018). In addition, gait and cognitive abnormalities have been shown to persist past self-reported symptom resolution (Berkner et al., 2017; Broglio et al., 2007; Howell et al., 2013). Objective and sensitive assessments of the impact of concussion may therefore be more useful at identifying the effects of this injury.

1.1.2 Cognition

Generally, cognition is defined as all processes through which knowledge is gained, retained and utilized (Kihlstrom, 2018). Cognition is comprised of domains such as executive function and attention that are essential to everyday life abilities such as learning, problem solving, and decision making. There is evidence to suggest that cognitive function is impacted after concussion. Impairments in memory, processing speed, attention, and executive function have been previously reported (Prince & Bruhns, 2017). Specifically, individuals with concussion score more poorly on assessments of these domains compared to healthy controls. Though recovery may differ across domains, return to baseline in cognitive function has been reported to occur by 90 days post-injury (Karr et al., 2014). However, these deficits are typically observed in sport-related concussions and the extent of cognitive impairment may differ in community-dwelling adults since cognitive performance can be impacted by factors such as demographic characteristics, psychosocial factors, the time since injury, the degree of injury, and the neuropsychological tests utilised (Dikmen et al., 2001).

Objective assessments of cognition are a necessary tool for evaluating concussion. Not only can objective testing identify subtle impairments and provide standardized results, but in certain populations, there may be a discrepancy between subjective symptom reporting and objective symptoms where subjective assessments reveal no impairment despite persisting deficits. In some cases, neurocognitive abnormalities have been shown to remain after resolution of reported somatic symptoms. Broglio et al. found that despite reporting symptom recovery, athletes had persisting impairments in memory, processing speed, and reaction time following a concussion (Broglio et al., 2007). In a study that examined neurocognitive performance in high school athletes using the ImPACT computerized test battery, concussed athletes who denied subjective symptoms performed worse on all four ImPACT test measures composite scores (verbal and visual memory, reaction time, and processing speed) than the control group (Fazio et al., 2007). These studies suggest that self-reporting of symptoms may be insufficient for assessing cognitive function and tracking recovery and highlight the importance of objective cognitive assessments. This section discusses some of the different domains of cognition, as well as factors that can affect cognitive function after concussion

Cognitive reserve

The impact of concussions on cognition may be affected by cognitive reserve, the brain’s ability to adapt to and respond to damage (De Beaumont et al., 2012; Stenberg et al., 2020).

The level of cognitive reserve is influenced by education level, lifestyle factors such as physical activity and diet, and genetics (Allen, 2019). The cognitive reserve theory states that cognitive reserve moderates the influence of brain injury on clinical outcomes. For example, in neurodegenerative diseases, the cognitive reserve theory has been effective at explaining the variability in cognitive outcomes between individuals following disease/injury (Stern, 2009). In these cases, an individual with higher cognitive reserve may be able to cope better with the outcomes of a brain injury than someone with lower cognitive reserve.

Factors that affect cognitive reserve and the resulting level of cognitive impairment may differ between community-dwelling adults and athletes, and therefore impact cognition post-concussion differently (Clare et al., 2017; Greene et al., 2019). For example, significant disparities in performance on domains of executive function in athletes compared to non-athletes have been documented in the healthy adult athlete literature, in which athletes perform significantly better on neuropsychological tests that assess executive function when compared to non-athletes (Hernández-Mendo et al., 2019; Vestberg et al., 2017; Voss et al., 2010). In community-dwelling adults with mild traumatic brain injury, low cognitive reserve is associated with greater vulnerability to reduced cognitive functioning (Stenberg et al., 2020). In another study that measured cognitive reserve using pre-morbid IQ, individuals with greater cognitive reserve had better initial post-injury cognitive function (Steward et al., 2018). In addition, individuals with a higher level of education have been found to display less vulnerability to cognitive impairments following TBI (Kesler et al., 2003). Therefore, because cognitive reserve can be unique to each individual and may influence the effects of concussion differently, it is important to study the effects of concussion in community-dwelling adults as studies in athletes may not be generalizable to this population.

Executive function

Executive function is comprised of a set of cognitive skills that include cognitive flexibility and attention that are necessary to plan, monitor and execute goal-directed complex actions (Diamond, 2013). Executive function is essential for successful everyday functioning as it relates to areas of planning, problem solving, and decision making among others (Garner, 2009). Deficits in executive function are the most common cognitive change following concussion.

There are several assessments of executive function. These include: tasks that require mental switching between subtasks or categories, such as the Wisconsin Card Sorting Test (WCST), Trail Making Test (TMT), and verbal fluency; tests that require higher cortical control to sustain and monitor attention over a long period of time, such as conventional tests of sustained attention like the Paced Auditory Serial Addition Test (PASAT); and conflict-inducing tasks, such as various Stroop test variants (Chan et al., 2008).

The TMT is a commonly used assessment to test a wide range of executive function abilities (Salthouse, 2011). It consists of two tasks: Part A requires the participant to connect circled numbers in sequential order; Part B requires the participant to connect circled numbers and letters in alternating order (ie. 1-A-2-B-3, etc). In both tasks, the score is the time required to finish the task (Salthouse, 2011). Several studies have found that patients with concussion perform worse on the TMT compared to healthy controls (Brooks et al., 1999; Stuss, Stethem, Hugenholtz, & Richard, 1989). Based on these findings, concussion seems to cause deficits in executive function that can impact cognitive flexibility and attention. In the real world, this can lead to challenges in everyday life and affect an individual's ability to make decisions, multi-task, and problem solve.

Processing speed

Processing speed refers to the ability to identify, manipulate, and respond to information (Holdnack et al., 2019). Poor processing speed has a downstream effect on many other cognitive abilities (Beaulieu-Bonneau et al., 2017). Processing speed affects almost all cognitive responses to task inputs and is tested by a wide variety of neuropsychological tests. Some researchers even claim that processing speed deficits may be at the root of practically all concussion-related attention problems, while others argue that deficits occur regardless of processing speed impairments following concussion (Beaulieu-Bonneau et al., 2017). Nevertheless, adequate processing speed is required for activities of daily life, as processing speed problems can impair cognitive processing in other areas (Silva & Lee, 2021).

Measures of processing speed include the TMT Part A, the PASAT, the Symbol Digit Modalities Test (SDMT), and the Symbol Search and Coding tasks from the WAIS-IV (Stebbins, 2007). Poor performance on these tests is typically seen in individuals with concussion. For example, a study found that performance on the processing speed component of the ImPACT assessment in high school and collegiate athletes was reduced two days post-injury compared to baseline (McClincy et al., 2006). The effects of concussion on processing speed have been investigated in other athletic populations with similar results (Collins et al., 1999; Covassin et al., 2010; Gronwall & Wrightson, 1975; Maddocks & Saling, 1996). Investigations of the impact of concussion on processing in community-dwelling adults are limited, despite the importance of processing speed in everyday life.

Attention

Some of the most reported cognitive changes following concussion are deficits in complex attention. Complex attention encompasses the subdomains of sustained, divided, and selective attention, as well as processing speed (Sachdev et al., 2014). Of particular interest are deficits in divided attention following concussion as deficits in this subdomain may be related to other areas impacted by concussion such as gait.

Divided attention refers to the ability to process multiple sources of information at once. Several older studies highlight impairments in divided attention following concussion as seen by poorer performance on tests such as the PASAT following concussion (Gronwall & Wrightson, 1974; Stuss, Stethem, Hugenholtz, Picton, et al., 1989; Vanderploeg et al., 2005). However, due to confounds such as (1) various cognitive loads imposed by different tests, (2) failure to account for time after injury, and (3) failure to control for processing speed deficiencies, older research is more likely to produce inconsistent results on whether or not concussion impairs divided attention.

More recent studies have found divided attention deficits that are independent of processing speed. For example, a study found that when the two activities were conducted simultaneously, the mTBI group exhibited impaired divided attention, but when the two tasks were completed separately, the two groups did not differ in performance (Park et al., 1999). Another study by Azouvi et al. found that impairments in divided attention were still present even when controlling for slow processing speed (Azouvi et al., 2008). Division of attention is required during many aspects of everyday life that involve completing tasks simultaneously. Understanding how these deficits manifest and what other areas of functioning they may impact is important for the management and treatment of concussion.

1.1.3 Gait

Gait is an important and complex daily activity. Normal gait requires optimal functioning in areas such as motor control, balance, and cognition. Healthy gait is essential for maintaining quality of life and personal independence and is an overall indicator of health. Common measures of gait include gait velocity, cadence, step length, and stride length. In healthy individuals, gait velocity is approximately 1.2 to 1.4 m/s, cadence ranges between 100 and 120 steps/min, step length is 60-70 cm, and stride length is typically between 130 to 145 cm (McKay et al., 2017). Changes in gait are typically seen with aging and in conditions that result in gait deficits, and objective gait assessments are useful for identifying these changes and monitoring disease progression and treatment.

When examining gait post-concussion, gait tasks and populations studied are varied and result in mixed findings with regards to how gait is impacted after injury. For example, some studies show that gait velocity decreases post-injury, while others report it remains unchanged (Fino et al., 2018). However, there is evidence to say that gait in individuals with concussion differs from healthy gait, with recovery occurring anywhere between 11–90 days post-concussion (Fino et al., 2018). Some studies also show changes in other spatiotemporal gait measures such as cadence and step length (Fino et al., 2018). Together, these findings imply that gait abnormality following concussion typically manifests as slower gait velocity and decreased cadence and step length.

Gait and cognition

Walking is not a completely automatic task as it involves a cognitive load needed for navigation and obstacle avoidance (Yogev-Seligmann et al., 2007). This relationship between cognition and gait has been widely studied in older adults and clinical populations. In normal aging, gait measures such as gait speed are associated with cognitive function, specifically with cognitive domains such as executive function and attention (Demnitz et al., 2016). Gait quality is also a predictor of future cognitive impairment in older adults (Toots et al., 2019). Similarly, poor cognitive functioning may be associated with changes in gait in populations with neurodegenerative diseases (Morris et al., 2016).

Gait is not a solely automatic task. Several pieces of evidence support the idea that safe and effective gait requires more than minimal higher cortical control. Several imagining studies have revealed activity of frontal and parietal activity areas during gait. For example, in a study that used Positron emission tomography (PET) to identify the areas of the brain involved in the imagination of gait-related tasks such as standing, initiating gait, and walking, activation was observed in the dorsal premotor cortex and precuneus bilaterally, the left dorsolateral prefrontal cortex, the left inferior parietal lobule, and the right posterior cingulate cortex (Malouin et al., 2003). In other studies that investigated the activation of brain areas during gait, significant activity was found in the supplementary motor area (SMA) and the prefrontal cortices (PFC) (Koenraadt et al., 2014). The SMA is generally known for its role in interlimb coordination or rhythmic arm and leg movements (Debaere et al., 2001). However, during gait the SMA is also involved in the selection, planning and coordination of movement (Sahyoun et al., 2004). In addition to being active during gait, activation of the PFC is also typically observed in attention demanding tasks and tasks that require walking while performing a secondary task (Holtzer et al., 2011). The SMA and PFC are both involved in executive function, and the PFC is involved in other cognitive functions such as attention (Ardila et al., 2018; Miller et al., 2002). These findings suggest that higher cortical control is not only involved in normal gait, but that when gait tasks necessitate increased cognitive and sensory information processing, higher brain areas become increasingly activated.

Several studies have examined the relationship between gait and cognition in clinical populations and older adults. The InChianti study is one such study that investigated the relationship between executive function and gait in older adults without dementia by having participants walk at a self-paced and fast speed over an obstacle course and assessing executive function using the TMT-B. The study found that individuals who performed poorer on the TMT-

B had a slower gait speed (Ble et al., 2005). Another study found similar results, with poor executive function and processing speed associated with lower gait velocity and higher double support time (Martin et al., 2013). This relationship has also been observed in individuals with Alzheimer's disease (Sheridan et al., 2003), mild cognitive impairment (Cosentino et al., 2020), and dementia (IJmker & Lamoth, 2012). Gait speed has also been frequently identified as a predictor for cognitive decline in older adults (Hoogendijk et al., 2020).

Dual-task paradigms provide further evidence that supports the involvement of cognition in gait. In this task, individuals walk while simultaneously performing a cognitive task. Because the dual-task requires cognitive functions such as executive function and attention, it can detect gait changes that may otherwise be undetected with a single task like normal walking (Strobach et al., 2018). If gait requires no cognitive input, then the addition of a cognitive task during walking should result in no changes; however, gait changes are present in healthy individuals during dual-task conditions (Ebersbach et al., 1995). Furthermore, individuals with cognitive impairment display greater gait impairments during the dual-task than healthy individuals. For example, patients with mild cognitive impairment or Alzheimer's disease walked slower and had increased stride time compared to cognitively healthy controls, whereas gait was not significantly different between groups in the single-task condition (Muir et al., 2012). Specifically, deficits in executive, attention, and processing speed have been associated with dual-task gait performance (MacAulay et al., 2014). Together, these findings suggest that gait is an attention demanding task that relies on executive function for the performance of two simultaneous tasks.

In studies that assess the relationship between gait and cognition, gait speed is a commonly used gait measure. However, despite its sensitivity to aging and to different neurodegenerative diseases and disorders, gait speed may not be discriminative or reflective of the subtle changes that occur in gait following concussion. Because of its clinical utility, gait speed is a widely used measure and is sometimes referred to as the “sixth vital sign” (Middleton et al., 2015); however, because of the complexity and multidimensionality of gait, it cannot be represented by a single construct. In addition, particularly in the area of traumatic brain injury, gait speed may not necessarily be sensitive on its own of the subtle changes in gait that may occur in response to concussive injury such as subtle deficits in cognition. Gait and gait characteristics are critical for discrimination of disease, as well as for identifying specific features of disease progression. Selective identification of gait characteristics is therefore critical for discriminating between different types of disease. Additionally, due to different levels of fitness and the potential neuroprotective effects of exercise, gait changes observed in athletes post-concussion may be different than in community-dwelling adults (Vecchio et al., 2018).

Cautious gait behaviour

Cautious gait behaviour is a gait pattern typically characterized by slower gait velocity and an increase in double support time. Double support time (DST), defined as the percentage of the gait cycle spent with both feet on the ground, is a more stable stance than parts of the gait cycle spent on one foot (Herssens et al., 2020). Cautious gait behaviour is a normal response during instances when gait is unstable; for example, healthy adults adopt this strategy when walking on slippery surfaces or during instances of divided attention such as walking while using a phone (Crowley et al., 2019). Figure 1 presents a hypothetical model of the relationship between performance/safety in everyday tasks and cautious gait behaviour. When adopted as part of a healthy response as previously mentioned, cautious gait behaviour allows for increased stability and safety. However, in older adults and clinical populations such as individuals with dementia, cautious gait behaviour tends to be excessive or abnormal, and is associated with an increase in risk of falls (Pirker & Katzenschlager, 2017). Some studies in older adults have also found the opposite, where a decrease in cautious gait behaviour is associated with falls, specifically when individuals with dementia may be experiencing impulsivity or agitation (Quach et al., 2011; Zhang et al., 2019). In cases such as these, cautious gait behaviour falls outside of the optimal range and is either higher or lower, resulting in increased risk to safety and performance.

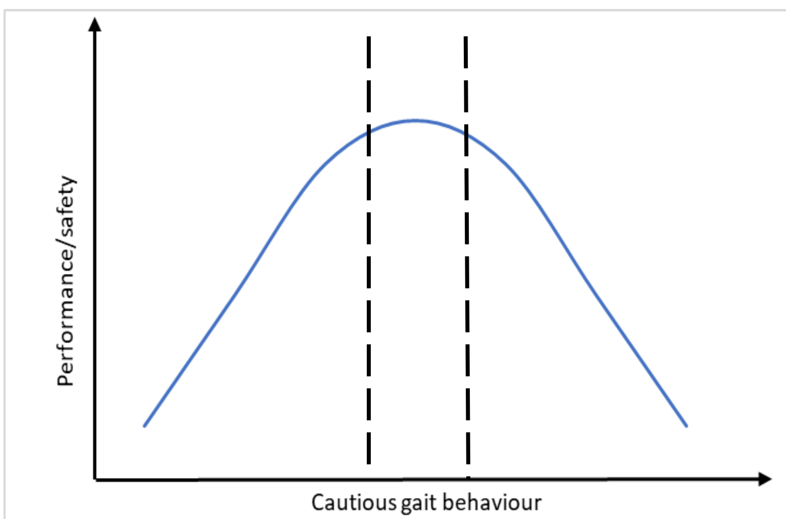

Figure 1. *A hypothetical model of the relationship between cautious gait behaviour and performance/safety in everyday tasks. The space between the dashed lines is considered to be the optimal level of cautious gait behaviour in healthy individuals.*

In certain situations, cautious gait behaviour may be a voluntary response such as in the case of walking on a slippery surface. However, in situations such as the dual-task, cautious gait behaviour may be an involuntary response caused by cognitive-motor interference. If gait is an attention-demanding task, the addition of a secondary task that also requires attention causes a deterioration in either or both tasks, according to the capacity sharing theory (Yogev-Seligmann et al., 2007). In cases where cognitive deficits may be present, the ability to divide and allocate attention between gait and the cognitive task may subsequently be impaired, resulting in cautious gait behaviour as well as errors in the cognitive task (Yogev-Seligmann et al., 2007). The capacity to attend to both tasks may also be limited by deficits in processing speed (Guttentag, 1989). Even in single-task walking, cautious gait behaviour may still be present. Single-task walking, which is considered to be mostly automatic, may become a more attention-demanding task after concussion (McCulloch, 2007).

The relationship between gait and cognition in concussion

As discussed, a concussion can result in changes in gait and cognition after injury. Together, deficits in these areas can result in cautious gait behaviour. The presence of cautious gait behaviour in individuals with concussion has been studied in collegiate student-athletes. A study found that individuals with a history of concussion have a slower gait velocity and increased time spent in double support, which the authors characterized as a 'conservative gait strategy' (Buckley et al., 2016). However, what the immediate impact of concussion is on cautious gait behaviour and what cautious gait behaviour looks like in community-dwelling adults is still unknown. Overly cautious gait behaviour may compromise safety in certain situations. Cautious gait behaviour is slower and less efficient (Zarrugh et al., 1974). While overly cautious gait may be safe in controlled laboratory settings, in everyday environments where there may be multiple obstacles, crowds, and tasks to complete simultaneously that require divided attention and intact executive function, safety may be compromised. Specifically, cautious gait behaviour may increase risk of falls, and interfere with successful completion of everyday tasks. Given previous evidence that implies cautious gait behaviour may still be present after the acute period of concussion, it is important to identify and characterize its presence immediately after concussion when its impact on safety may be the highest and to monitor how it changes over time. Establishing the relationship between gait and cognition by way of examining cautious gait behaviour may provide clinicians with a more sensitive outcome of often subtle deficits in gait and cognition which can then be targeted for the management and treatment of concussion.

1.2 Rationale and objective

Cautious gait behaviour has been studied in populations such as older adults and those with cognitive decline. It is characterized by certain changes in gait that may reflect deficits within certain cognitive domains such as executive function and attention. Deficits within these domains are expected to result in increased cautious gait behaviour. In community-dwelling individuals with concussion, the relationship between gait and cognition, and the potential outcome of this relationship as cautious gait behaviour, has yet to be clearly investigated despite the possible implications for safety. In addition, while it is understood that factors such as age and symptom severity can impact gait and cognition, it is unclear how these factors affect cautious gait behaviour or its recovery. What specific cognitive domains are related to gait measures and whether performance in certain domains can predict recovery of cautious gait behaviour is also unknown. A conceptual model of these literature gaps is presented in Figure 2.

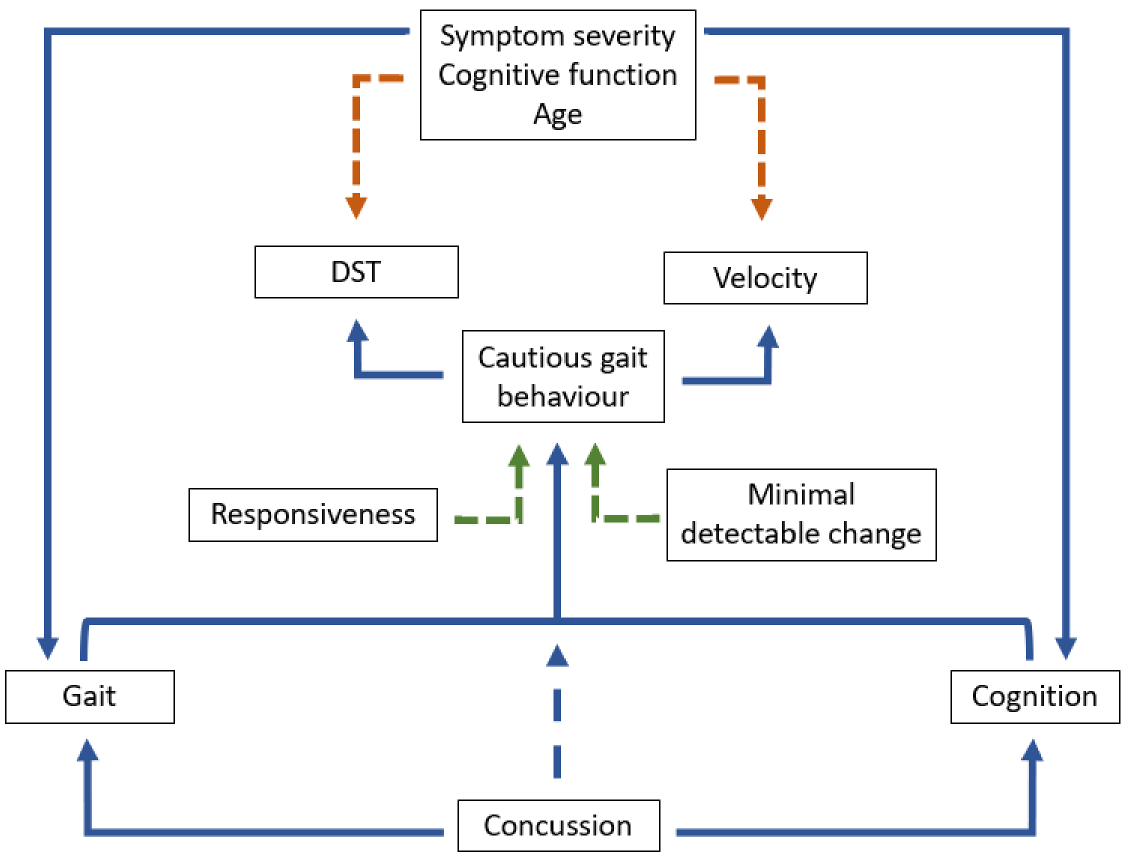

Figure 2. *A conceptual model presenting an overview of the thesis. Known relationships are presented in solid lines. Dashed lines represent relationships that are less established in the literature and will be the focus of this thesis. Orange arrows are relationships that will examined in Study 1 and 2 at a cross-sectional and longitudinal level. Green arrows represent concepts that will be examined in Study 2.*

Given the incidence of concussion and the lack of research that investigates the effect of this injury in community-dwelling adults, addressing this literature gap is important. To improve our understanding of the effects of concussion in community-dwelling adults, this thesis then aims to understand how concussion affects the relationship between gait and cognition by examining cautious gait behaviour in two related studies.

Study 1: Cross-Sectional Analysis of Gait and Cognitive Changes Following Concussion

The purpose of this study is to determine whether individuals with concussion demonstrate cautious gait behaviour acutely (within 7 days of injury) in comparison to healthy controls. This study will also aim to determine whether gait and gait behaviour characteristics differ according to symptom severity scores and according to neuropsychological tests of cognition. By employing gait conditions of increasing cognitive load, the relationship between gait and cognition can be assessed.

Given the relationship between gait and cognition and the effect of dual-tasks on gait, it is hypothesized that individuals with concussion will display more cautious gait behaviour than the healthy control group during the cognitive-motor tasks. When partitioning the Concussion Group by their symptom severity scores, individuals with concussion who score higher on the SCAT3 Symptom Severity Scale will show increased cautious gait behaviour compared to individuals who score lower on the SCAT3 Symptom Severity Scale and the Healthy Group. Additionally, partitioning the Concussion Group by cognitive scores is expected to show that individuals who scored below average on neuropsychological tests of cognition will show increased cautious gait behaviour compared to the Healthy Group. This cautious gait behaviour will be characterized by increased time spent in double support and decreased gait velocity, cadence, and step length, with the largest cautious gait behaviour observed during the gait task with the greatest cognitive load.

Study 2: Longitudinal Analysis of Cognitive and Gait Recovery

The purpose of this study is to investigate recovery of gait and cognition from Week 1 post-injury to Week 12. This will be carried out via three approaches:

1. The responsiveness of the gait measures used will be assessed using effect sizes such as the standard response mean (SRM).
2. The Minimal Detectable Change (MDC) values will be calculated for the gait measures to find the minimal amount of change not due to error between Week 1 and 12. Individuals will then be characterized according to criteria based on the MDC scores and the Healthy Group's 95 confidence intervals.
3. Predictors of recovery will be analyzed.

Based on previous literature that identified higher double support time and lower velocity in individuals with concussion compared to healthy controls past the acute period of injury, it is hypothesized that double support time and velocity will be most responsive to change compared to cadence and step length. Symptom severity, processing speed and executive function are expected to be predictors of recovery at Week 12 in the Concussion Group.

Chapter 2: Cross-sectional analysis of the effect of concussion on cautious gait behaviour

2.1 Abstract

Gait and cognition are commonly affected after concussion, however the relationship between these two domains has yet to be investigated in community-dwelling adults with concussion. The purpose of this study is to examine the relationship between gait and cognition by investigating the effect of concussion on cautious gait behaviour. To do so, double support time (DST), cadence, velocity and step length were compared across three conditions of increasing cognitive load: Self-paced, Talking, and Dual-task. In addition, the effect of symptom severity and neuropsychological test performance on cautious gait behaviour was analyzed in 65 participants with concussion and 15 healthy controls. Results revealed main effects of group for DST and cadence. A main effect of condition was observed for all gait measures. In addition, individuals with higher symptom severity scores and those with below average performance on cognitive tests showed more cautious gait behaviour compared to the Healthy Group. The increased cautious gait behaviour observed during the Dual-task suggests the presence of subtle cognitive impairments in domains such as attention and executive function. Additionally, because no significant group effects were found for velocity, a commonly assessed gait measure and indicator of health in other pathologies, it is possible that DST and cadence are more sensitive to gait and cognitive changes in concussion. The results of this study can help clinicians address gait and cognitive impairments by targeting cautious gait behaviour for treatment.

2.2 Introduction

A concussion is a mild traumatic brain injury that is caused by a hit to the head, neck or face or body that causes movement of the brain inside the skull, leading to injury (Mccrory et al., 2017). Changes in gait and cognition are common post-injury and may impair day-to-day functioning. When examining gait post-concussion, gait tasks and populations studied are varied and result in mixed findings with regards to how gait is impacted after injury. For example, some studies show that gait velocity decreases post-injury, while others report it remains unchanged (Fino et al., 2018). However, there is evidence to say that gait in individuals with concussion differs from healthy gait (Fino et al., 2018).

Walking is not a completely automatic task as it involves a cognitive load needed for navigation and obstacle avoidance (Yogev-Seligmann et al., 2007). This relationship between cognition and gait has been widely studied in older adults and clinical populations. In normal aging, gait measures such as gait speed are associated with cognitive function, specifically with cognitive domains such as executive function and attention which may be impacted after concussion (Prince & Bruhns, 2017). The motor-cognitive dual-task is a typical paradigm for studying the links between gait and cognition. Because the dual-task challenges cognitive domains like executive function, it can detect alterations in gait that would otherwise go undetected with a single task like regular walking (Strobach et al., 2018).

Cautious gait behaviour is a normal response during instances when gait is unstable (Crowley et al., 2019). This strategy is typically characterized by slower gait velocity and an increase in double support time (DST). Double support time, defined as the percentage of the gait cycle spent with both feet on the ground, is a more stable stance than parts of the gait cycle spent on one foot (Herssens et al., 2020). Given the stability of higher double support time, a cautious gait strategy may be a safety response during instability in healthy individuals that may be consciously controlled. However, individuals with concussion may present with a higher degree of cautious gait behaviour that may be influenced by cognitive function.

Individuals may develop cognitive abnormalities shortly after a concussion, which may raise cognitive strain and change walking patterns. Cautious gait behaviour has been investigated in collegiate student-athletes with concussion. In a study by Buckley et al., athletes with a history of concussion were characterized as having a “conservative gait strategy”. The immediate effects of concussion on cautious gait behaviour, however, have yet to be investigated. Investigations of changes in gait and cognition and the relationship between them are limited in community-dwelling adults. Given that in Canada the majority of concussions are caused by non-sports related injuries (Public Health Agency of Canada, 2020), it is important to improve our understanding of the effects of concussion in community-dwelling adult.

Therefore, the purpose of this study is to determine whether individuals with concussion demonstrate cautious gait behaviour acutely (within 7 days of injury) in comparison to healthy controls. This study will also aim to understand the impact of symptom severity and cognitive performance on cautious gait behaviour. It is hypothesized that individuals with concussion will display more cautious gait behaviour than the healthy control group during the cognitive-motor tasks. When dividing the Concussion Group by their symptom severity scores, individuals with concussion who score higher on the SCAT3 Symptom Severity Scale will show increased cautious gait behaviour compared to individuals who score lower on the SCAT3

Symptom Severity Scale and the Healthy Group. Additionally, dividing the Concussion Group by cognitive scores is expected to show that individuals who score below average on neuropsychological tests of cognition, will show increased cautious gait behaviour compared to the Healthy Group. This cautious gait behaviour will be characterized by increased time spent in double support and decreased gait velocity, cadence, and step length, with the largest cautious gait behaviour observed during the Dual-task.

2.3 Methods

This was a retrospective analysis of data that were collected at the Hull-Ellis Concussion and Research Clinic at the Toronto Rehabilitation Institute where individuals with concussion were referred from 5 partnering emergency departments in Toronto. Data were collected from February 2016 to September 2019. Healthy control data were also collected. Patients were assessed within the first 7 days of injury to mark Week 1 and were subsequently re-assessed at weeks 2, 4, 8, 12, and 16 post injury.

Demographic data collected for both the Concussion and Healthy Group included: age, sex, height, previous health conditions, and years of education. In addition, the following information was collected for the Concussion Group: weight, history of previous concussion, prior mental health conditions, time to first appointment after injury, and prior migraine headaches.

Exclusion and inclusion criteria for the Concussion Group are listed in Table 1. Healthy controls were excluded if they had a history of concussion or other neurological conditions, musculoskeletal injuries, or vestibular disorders within one year of assessment that may affect gait. Because weight data was not collected for the Healthy Group, it was assumed that the participants had a BMI lower than 30.

Table 1. *Inclusion and exclusion criteria for the Concussion Group.*

Inclusion criteria	Exclusion criteria
• 17-85 years of age • Diagnosed with a concussion by an ED physician • Glasgow Coma Score of 13-15 • No focal neurological findings or positive neuroimaging finding (or imaging was deemed unnecessary on CT scan decision rules in ED) • Participant is willing to come to first appointment within 7 days of injury • Sufficient proficiency in English to be able to complete questionnaires and tools used in study i.e. Grade 6 or above reading level	• Community physician referrals • Injury occurred greater than seven days to first Hull-Ellis physician-assessment • Injury occurred as the result of a work-place injury or motor-vehicle collision (MVC) • Positive image or Neurological findings • Symptomatic from a previous concussion in the last three months or less • In patient admission • Ongoing or history of MSK injury within one year of assessment* • BMI > 29.9

**previous joint replacement surgery, previous orthopaedic surgery, previous lower limb condition/injury (causing muscle or joint discomfort or reduced range of motion), or previous back pain/injury*

2.3.1 Assessments

To collect gait data, participants walked across a GAITRite mat to collect a minimum of 16 footfalls (CIR Systems Inc, Havertown, PA) in three conditions of progressively increasing cognitive load: Self-paced, Talking, and Dual-task. The Self-paced condition had no explicit cognitive load and required participants walked across the mat at a self-selected speed. The cognitive tasks were the Talking and Dual-task conditions. In the Talking condition, participants walked across the mat at a self-paced speed while counting upwards by one from a three-digit number. The Dual-task condition required participants to walk across the mat at a self-paced speed while counting backwards by seven from a three-digit number (Manning, 1982).

Measures of interest included velocity (cm/s), cadence (steps/min), step length (cm), and double support time (% gait cycle). Velocity and step length were normalized to participant height as leg length information was not collected.

The Concussion Group completed the Concussion Assessment Tool Edition 3 (SCAT3) (Guskiewicz et al., 2013), a standardized tool used to evaluate injured athletes for concussion, during every visit. Patients self-reported symptom severity on 22 symptoms using the SCAT3 symptom evaluation, where they rated each symptom from 0 (none) to 5-6 (severe), for a maximum possible score of 132.

Cognitive data were collected at Week 1, 2, and 12 using two neuropsychological tests: the Trail Making Test Parts A & B (TMT-A & B) (Stebbins, 2007), and the Coding and Symbol search subtests from the WAIS-IV (Lichtenberger et al., 2012). The Coding and Symbol search subtests were corrected for age and combined into a composite score called the Processing Speed Index (PSI) (Weiss et al., 2019). The Trail Making Test Parts A & B were corrected for age, sex, and education level. The TMT-A and the PSI primarily assess processing speed, and the TMT-B assesses executive function. Executive function is a set of cognitive skills that include cognitive flexibility and attention that are necessary to plan, monitor and execute goal-directed complex actions (Sira & Mateer, 2014). Executive function was chosen as a cognitive domain of interest because changes in gait during motor-cognitive dual-tasks rely on executive functions since performance during these tasks requires the ability to effectively allocate attention between tasks that are performed simultaneously (Allali et al., 2008). Processing speed refers to the speed at which information can be processed and responded to and is related to the ability to efficiently use other cognitive abilities (Drozdick et al., 2013). In the motor-cognitive dual-tasks, processing speed is vital to the ability to complete the cognitive task while walking, and the ability to perform processes of executive function such as division of attention. The Healthy Group did not complete any of the cognitive assessments.

2.3.2 Statistical Analysis

All statistical analyses were completed using SPSS v28 (IBM, Armonk USA). Statistical significance was set at p = .05. Normality of the data was checked using Shapiro-Wilk Normality tests. All gait variables, except velocity, failed normality according to the Shapiro–Wilk test and were subsequently log-transformed and retested to assess normality. The assumption of sphericity was violated for all analyses according to Mauchly's test, and the Greenhouse-Geisser correction for degrees of freedom was used. The following statistical analyses were carried out:

Comparison of the Concussion and Healthy Group. Individuals with concussion were matched to the healthy controls on age and sex. To test the hypothesis that the Concussion Group would display more cautious gait behaviour than the Healthy Group, a 2 × 3 mixed ANOVA was conducted to assess the main effects of group (Healthy, Concussion) and condition (Self-paced, Talking, Dual-task).

Subdivision of the Concussion Group by SCAT3 symptom severity scores. To explore the relationship between concussion symptom severity and spatiotemporal measures of gait, the Concussion Group was divided into two groups using a median split of the total SCAT3 symptom severity score. To test the hypothesis that symptom severity is related to cautious gait behaviour, a 3 × 3 mixed ANOVA was used to assess the main effects of group (Healthy, LOW SCAT3, HIGH SCAT3) and condition (Self-paced, Talking, Dual-task) for each gait measure.

Subdivision of the Concussion Group by cognitive scores. To assess the relationship between cognitive performance and gait quality, individuals who scored below average according to Weschler classification ranges (Iverson, 2011) for each of the cognitive tests in the Concussion Group were analyzed. Individuals who scored above average were excluded from the analyses. To test the hypothesis that poor cognitive function results in increased cautious gait behaviour, a 2 × 3 mixed ANOVA was conducted for each gait measure to examine the main effects of group (Healthy, Concussion) and condition (Self-paced, Talking, Dual-task) for each cognitive measure.

The number of responses, errors and error rate (number of errors/number of responses) during the Dual-task condition were also assessed for each analysis. The number of responses was analyzed using independent samples t-tests for two group comparisons between the healthy and Concussion Group and in the cognitive subdivision analyses, and one-way ANOVAs for the SCAT3 subdivision analysis. Due to violations of the assumption of normality, the Mann-Whitney U test was used for differences in error rate and number of errors for the two group comparisons between the healthy and Concussion Group and in the cognitive subdivision analyses. The Kruskal-Wallis H Test was used to analyze differences in the number of errors and error rate in the SCAT3 subdivision analysis.

2.4 Results

2.4.1 Participant characteristics

254 participants (32.2 ± 11.7 years, 152 females) with concussion were eligible to be included in this study. From the 254 participants, 65 sex and age matched concussion individuals were found for the 15 healthy controls and used for analysis. The Concussion and Healthy Group participant characteristics are summarized in Table 2. Scores for the TMT-A, TMT-B, and PSI in the Concussion Group fall within normative reference values (Psychcorp, 2020; Tombaugh, 2004). Demographic information for the subdivision of the Concussion Group by cognitive scores and symptom severity scores are presented in Tables 3 and 4.

Table 2. *Demographic information for the Concussion and Healthy Group.*

Variable	Concussion (n=65)	Healthy (n=15)
Age [Mean (SD)]	27.9 (7.4)	31.3 (11.2)
Sex [Number (%)]		
Males	16 (24.6)	6 (40)
Females	49 (75.4)	9 (60)
Education level		
Less than high school diploma	1	0
High school diploma	5	1
Incomplete postsecondary studies	4	0
Trade certificate/diploma or College, CEGEP, or other non-university certificate/diploma	7	3
Bachelor's degree	39	3
Master's degree	9	8
PhD	0	0
SCAT3 Symptom Severity Subscale total score [Median (range)]	43 (4-128)	N/A
Processing Speed Index [Mean (SD)]	103.4 (12.6)	N/A
TMT-A T-Score [Mean (SD)]	43.8 (8.9)	N/A
TMT-B T-Score [Mean (SD)]	46.4 (8.8)	N/A

Table 3. *Demographic information for the subdivision by symptom severity scores analyses.*

Variable	**LOW SCAT3 (n=32)**	**HIGH SCAT3 (n=33)**
Age [Mean (SD)]	28.1 (7.4)	27.6 (7.4)
Sex [Number (%)]		
Males	9 (28.1)	7 (21.2)
Females	23 (71.9)	26 (78.8)
Education level		
Less than high school diploma	1	0
High school diploma	0	5
Incomplete postsecondary studies	3	1
Trade certificate/diploma or College, CEGEP, or other non-university certificate/diploma	2	5
Bachelor's degree	21	18
Master's degree	5	4
PhD	0	0

Table 4. *Demographic information for the subdivision by cognitive scores analyses.*

Variable	**LOW TMT-A (n=30)**	**LOW TMT-B (n=24)**	**LOW PSI (n=9)**
Age [Mean (SD)]	26.3 (4.2)	28.2 (6.3)	26.2 (9.6)
Sex [Number (%)]			
Males	10 (33.3)	3 (12.5)	4 (44.4)
Females	20 (66.7)	21 (87.5)	5 (55.5)
Education level			
Less than high school diploma	0	0	1
High school diploma	4	0	1
Incomplete postsecondary studies	0	0	0
Trade certificate/diploma or College, CEGEP, or other non-university certificate/diploma	3	3	1
Bachelor's degree	16	18	5
Master's degree	7	4	1
PhD	0	0	0

2.4.2 Analysis of variance

Across all conditions, DST ranged from 16.5 to 41.1% in the Concussion Group and 19 to 33.7% in the Healthy Group. Normalized velocity ranged from 0.27 to 1.07 cm/s/cm in the Concussion Group and 0.45 to 0.93 cm/s/cm in the Healthy Group. In the Concussion group, cadence ranged from 63.6 to 132.6 steps/min, and in the Healthy group it ranged from 87.1 to 125.8 steps/min. Normalized step length ranged from 23% to 49% in the Concussion Group and 31% to 48% in the Healthy Group. Scatter plots for the gait measures across the different conditions are presented in Figure 3 for the Concussion Group and Healthy Group.

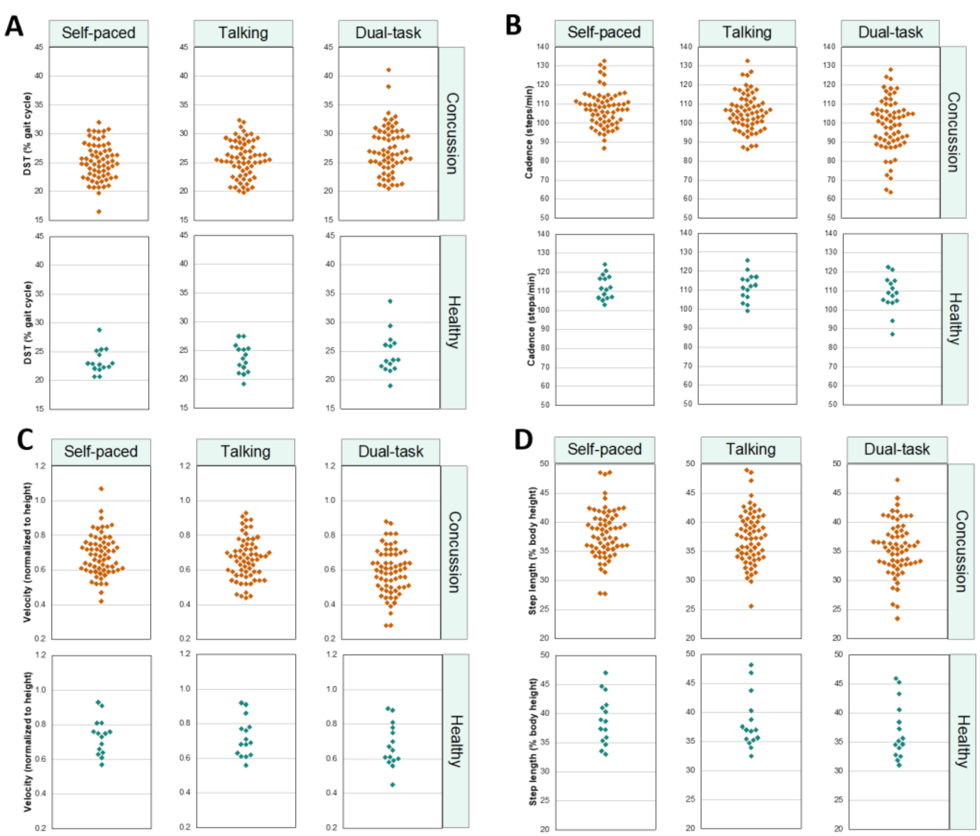

Figure 3. *Scatter plots of gait measures in the Self-paced, Talking, and Dual-task conditions in the Concussion and Healthy Group. A) DST (% gait cycle). B) Cadence (steps/minute). C) Velocity (cm/s normalized to body height). D) Step length (% body height).*

2.4.3 Comparison of the Concussion and Healthy Group

DST was significantly higher in the Concussion Group compared to the Healthy Group [$F(1, 78) = 5.696$, $p = .019$, $\eta^2 = 0.068$]. A main effect of condition was observed for DST [$F(1.636, 127.647) = 17.169$, $p < .001$, $\eta^2 = 0.151$]. Bonferroni adjusted post-hoc analysis identified significantly larger double support time in the Dual-task compared to the Talking ($p < .001$) and Self-paced ($p < .001$) conditions (Figure 4A). A main effect of group was observed for cadence [$F(1, 78) = 6.260$, $p = .014$, $\eta^2 = 0.074$], as well as a main effect of condition [$F(1.193, 93.03) = 13.848$, $p < .001$, $\eta^2 = 0.151$], where cadence was lower in the Concussion Group compared to the Healthy Group. Bonferroni adjusted post-hoc analysis identified significantly lower cadence in the Dual-task compared to Talking ($p < .001$) and Self-paced ($p < .001$) conditions (Figure 4B). No significant group effects were observed for velocity or step length; however, there was a significant effect of condition, with significant differences observed across all pairwise comparisons (Figure 4C-D). No significant group×condition interactions were identified for any of the gait measures. ANOVA results are presented in Table 5.

There was a statistically significant difference in the number of responses during the Dual-task between the Healthy and Concussion Group, with greater responses in the Healthy Group [0.23 (95% CI, 0.078 to 0.38), $t(77) = 3.043$, $p = .003$]. The error rate did not differ between groups (Mann-Whitney $U = 589$, $z = -1.505$, $p = .132$). The number of errors also did not differ between groups (Mann-Whitney $U = 577$, $z = -1.245$, $p = .213$).

Table 5. *ANOVA table for the comparison of the Concussion Group and Healthy Group.*

	Measure	Sum of Squares	df	F	Sig.	η^2
Intercept	DST	283.925	1, 78	33411.918	<.001***	.998
	Velocity	67.259	1, 78	1691.677	<.001***	.956
	Cadence	602.126	1, 78	125311.751	<.001***	.999
	Step length	26.909	1, 78	3480.824	<.001***	.978
Group	DST	.048	1, 78	5.696	.019*	.068
	Velocity	.133	1, 78	3.341	.071	.041
	Cadence	.030	1, 78	6.260	.014*	.074
	Step length	.004	1, 78	.561	.456	.007
Condition	DST	.018	1.636, 127.647	13.835	<.001***	.151
	Velocity	.157	1.328, 103.571	28.870	<.001***	.270
	Cadence	.023	1.193, 93.030	13.848	<.001***	.151
	Step length	.020	1.381, 107.70	32.580	<.001***	.295
Condition * group	DST	.002	1.636, 127.647	1.163	.308	.015
	Velocity	.010	1.328, 103.571	1.759	.187	.022
	Cadence	.003	1.193, 93.030	2.123	.145	.027
	Step length	0.000356	1.381, 107.70	.591	.495	.008

'***' $p < .001$, '**' $p < .01$, '*' $p < .05$

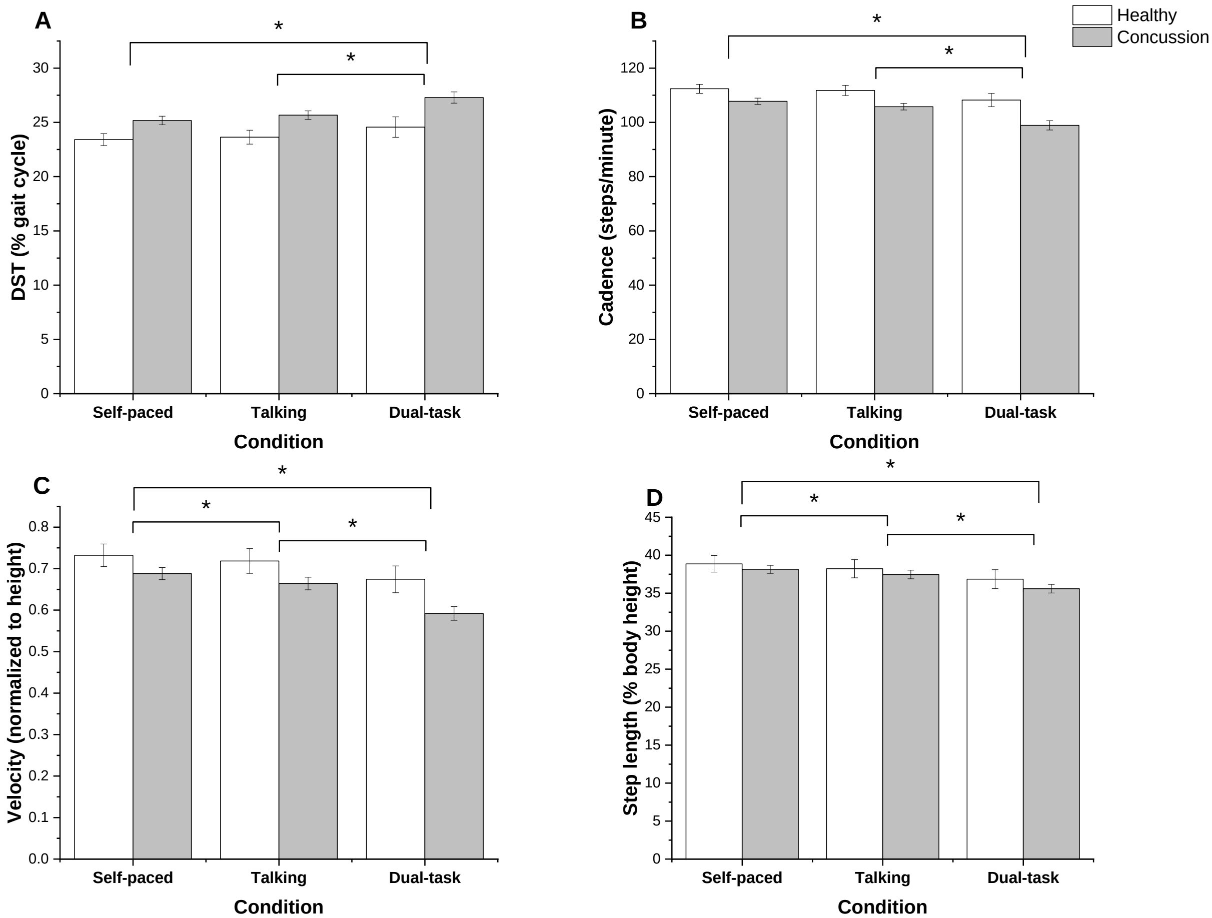

Figure 4. *Comparison of gait measure means across Self-paced, Talking and Dual-task conditions between the Healthy and Concussion Group. Values are represented as means and SE. Statistically significant condition differences are denoted by *. A) DST (% gait cycle). B) Cadence (steps/minute). C) Velocity (cm/s normalized to body height). D) Step length (% body height).*

2.4.4 Subdivision of the Concussion Group by SCAT3 symptom severity scores

A main effect of group was observed for DST [$F(2, 77) = 5.403$, $p = .006$, $\eta^2 = 0.123$]. Bonferroni adjusted post-hoc analysis identified significantly higher DST in the HIGH SCAT3 group compared to the Healthy Group ($p = .008$). Group differences were observed for cadence [$F(2, 77) = 3.208$, $p = .046$, $\eta^2 = 0.077$]. Bonferroni adjusted post-hoc analysis identified significantly lower cadence in the HIGH SCAT3 group compared to the Healthy Group (p = .047). A main effect of condition was identified for all gait measures. No group differences were observed for velocity or step length. No significant group×condition interactions were identified for any of the gait measures. ANOVA results are summarized in Table 6.

Error rate distributions were similar for all groups, as assessed by visual inspection of a boxplot. Median error rates were not statistically significantly different between groups [$\chi^2(2)$ = 4.038, p = .133]. The number of errors was also not significantly different between groups [$\chi^2(2)$ = 3.069, p = .165]. The number of responses during the Dual-task was statistically significantly different between the three groups [$F(2, 76) = 4.913$, p = .01, $\eta^2 = 0.114$]. Tukey post-hoc analysis revealed that the number of responses was significantly higher in the Healthy Group (10.6 ± 4.1) than in the LOW SCAT3 group (7.3 ± 4.2) and the HIGH SCAT3 group (6.9 ± 4.6).

Table 6. *ANOVA table for the subdivision by symptom severity scores analyses.*

	Measure	Sum of Squares	df	F	Sig.	η^2
Intercept	DST	412.286	1, 77	50899.442	<.001***	.998
	Velocity	94.052	1, 77	2397.111	<.001***	.969
	Cadence	862.903	1, 77	177784.522	<.001***	1.000
	Step length	39.052	1, 77	5176.542	<.001***	.985
Group	DST	.088	2, 77	5.403	.006**	.123
	Velocity	.213	2, 77	2.713	.073	.066
	Cadence	.031	2, 77	3.208	.046*	.077
	Step length	.026	2, 77	1.750	.181	.043
Condition	DST	.031	1.628, 125.340	23.720	<.001***	.236
	Velocity	.264	1.308, 100.749	48.487	<.001***	.386
	Cadence	.042	1.179, 90.813	25.299	<.001***	.247
	Step Length	.031	1.373, 105.689	50.677	<.001***	.397
condition * group	DST	.002	3.256, 125.340	.787	.512	.020
	Velocity	.013	2.617, 100.749	1.225	.303	.031
	Cadence	.004	2.359, 90.813	1.338	.268	.034
	Step length	.001	2.745, 105.689	.458	.696	.012

‘***’ $p < .001$, ‘**’ $p < .01$, ‘*’ $p < .05$

2.4.5 Subdivision of the Concussion Group by cognitive scores

No group×condition interaction effects were observed for any of the ANOVA analyses below.

TMT-A. DST was significantly higher [$F(1, 43) = 5.663$, $p = .022$, $\eta^2 = 0.116$], and cadence was significantly lower [$F(1, 43) = 5.84$, $p = .02$, $\eta^2 = 0.12$] in the LOW TMT-A group than the Healthy Group. A main effect of condition was observed for all gait measures. Results of the ANOVA are presented in Table 7.

There was a statistically significant difference in the number of responses during the Dual-task between the Healthy and Concussion Group, with greater responses in the Healthy

Group [0.22 (95% CI, 0.061 to 0.38), t(43) = 2.774, *p* = .008]. The error rate did not differ between groups (Mann-Whitney U = 276, z = -1.381, *p* = .167). The number of errors also did not differ between groups (Mann-Whitney U = 267, z = -1.161, *p* = .246).

Table 7. *ANOVA table for the analysis of subdivision by TMT-A scores.*

	Measure	Sum of Squares	df	F	Sig.	η^2
Intercept	DST	233.073	1, 43	32071.577	<.001***	.999
	Velocity	54.618	1, 43	1291.859	<.001***	.968
	Cadence	494.011	1, 43	115549.858	<.001***	1.000
	Step length	22.323	1, 43	2380.957	<.001***	.982
Group	DST	.041	1, 43	5.663	.022*	.116
	Velocity	.136	1, 43	3.212	.080	.070
	Cadence	.025	1, 43	5.840	.020*	.120
	Step length	.007	1, 43	.783	.381	.018
Condition	DST	.011	1.423, 61.195	13.482	<.001***	.239
	Velocity	.105	1.411, 60.658	28.669	<.001***	.400
	Cadence	.014	1.265, 54.377	14.583	<.001***	.253
	Step Length	.014	1.530, 65.782	32.458	<.001***	.430
condition * group	DST	0.000388	1.423, 61.195	.471	.562	.011
	Velocity	.003	1.411, 60.658	.793	.417	.018
	Cadence	.001	1.265, 54.377	1.334	.262	.030
	Step length	0.000088	1.530, 65.782	.203	.757	.005

'***' $p < .001$, '**' $p < .01$, '*' $p < .05$

TMT-B. DST was significantly higher [$F(1, 37) = 5.321$, $p = .027$, $\eta^2 = 0.126$], cadence was significantly lower [$F(1, 37) = 9.371$, $p = .004$, $\eta^2 = 0.202$], and velocity was significantly lower [$F(1, 37) = 4.689$, $p = .037$, $\eta^2 = 0.112$] in the LOW TMT-B group than the Healthy Group. There was a main effect of condition for all the gait measures. The full ANOVA findings are summarized in Table 8.

There was a statistically significant difference in the number of responses during the Dual-task between the Healthy and Concussion Group, with greater responses in the Healthy Group [0.35 (95% CI, 0.17 to 0.52), t(37) = 4.063, $p < .001$]. The error rate was not significantly different between groups (Mann-Whitney U = 246.5, z = 2.065, $p = .054$). The number of errors did not differ between groups (Mann-Whitney U = 235, z = 1.766, $p = .116$).

Table 8. *ANOVA table for the analysis of subdivision by TMT-B scores.*

	Measure	Sum of Squares	df	F	Sig.	η^2
Intercept	DST	215.777	1, 37	24504.921	<.001***	.998
	Velocity	49.786	1, 37	1469.531	<.001***	.975
	Cadence	454.697	1, 37	127833.879	<.001***	1.000
	Step length	20.561	1, 37	2596.78	<.001***	.986
Group	DST	.047	1, 37	5.321	.027*	.126
	Velocity	.159	1, 37	4.689	.037*	.112
	Cadence	.033	1, 37	9.371	.004**	.202
	Step length	.006	1, 37	.757	.390	.020
Condition	DST	.017	1.303, 48.214	15.354	<.001***	.293
	Velocity	.144	1.304, 48.264	28.494	<.001***	.435
	Cadence	.024	1.165, 43.089	15.338	<.001***	.293
	Step Length	.018	1.289, 47.702	24.696	<.001***	.400
condition * group	DST	.002	1.303, 48.214	2.119	.147	.054
	Velocity	.014	1.304, 48.264	2.853	.088	.072
	Cadence	.005	1.165, 43.089	3.534	.061	.087
	Step length	.001	1.289, 47.702	1.183	.296	.031

'***' $p < .001$, '**' $p < .01$, '*' $p < .05$

PSI. Significantly lower cadence [$F(1, 22) = 7.604$, $p = .011$, $\eta^2 = 0.257$] was observed in the LOW PSI group compared to the Healthy Group. A main effect of condition was observed for all gait measures. ANOVA results are presented in Table 9.

There was a statistically significant difference in the number of responses during the Dual-task between the Healthy and Concussion Group, with greater responses in the Healthy Group [0.33 (95% CI, 0.11 to 0.55), t(22) = 3.147, $p = .005$]. The error rate was not significantly different between groups (Mann-Whitney U = 94.5, z = 1.8, $p = .108$). The number of errors did not differ between groups (Mann-Whitney U = 95, z = 1.842, $p = .108$).

Table 9. *ANOVA table for the analysis of subdivision by PSI scores.*

	Measure	Sum of Squares	df	F	Sig.	η^2
Intercept	DST	130.734	1, 22	18015.193	<.001***	.999
	Velocity	30.941	1, 22	817.199	<.001***	.974
	Cadence	277.299	1, 22	114024.272	<.001***	1.000
	Step length	12.288	1, 22	1448.982	<.001***	.985
Group	DST	.018	1, 22	2.548	.125	.104
	Velocity	.066	1, 22	1.740	.201	.073
	Cadence	.018	1, 22	7.604	.011*	.257
	Step length	.001	1, 22	.081	.779	.004
Condition	DST	.007	1.601, 35.229	8.832	.002	.286
	Velocity	.049	1.619, 35.611	16.066	<.001***	.422
	Cadence	.006	1.444, 31.759	12.974	<.001***	.371
	Step Length	.007	1.588, 34.931	12.903	<.001***	.370
condition * group	DST	.000280	1.601, 35.229	.372	.645	.017
	Velocity	.000495	1.619, 35.611	.161	.807	.007
	Cadence	.000147	1.444, 31.759	.344	.641	.015
	Step length	.00069	1.588, 34.931	.128	.834	.006

‘***’ $p < .001$, ‘**’ $p < .01$, ‘*’ $p < .05$

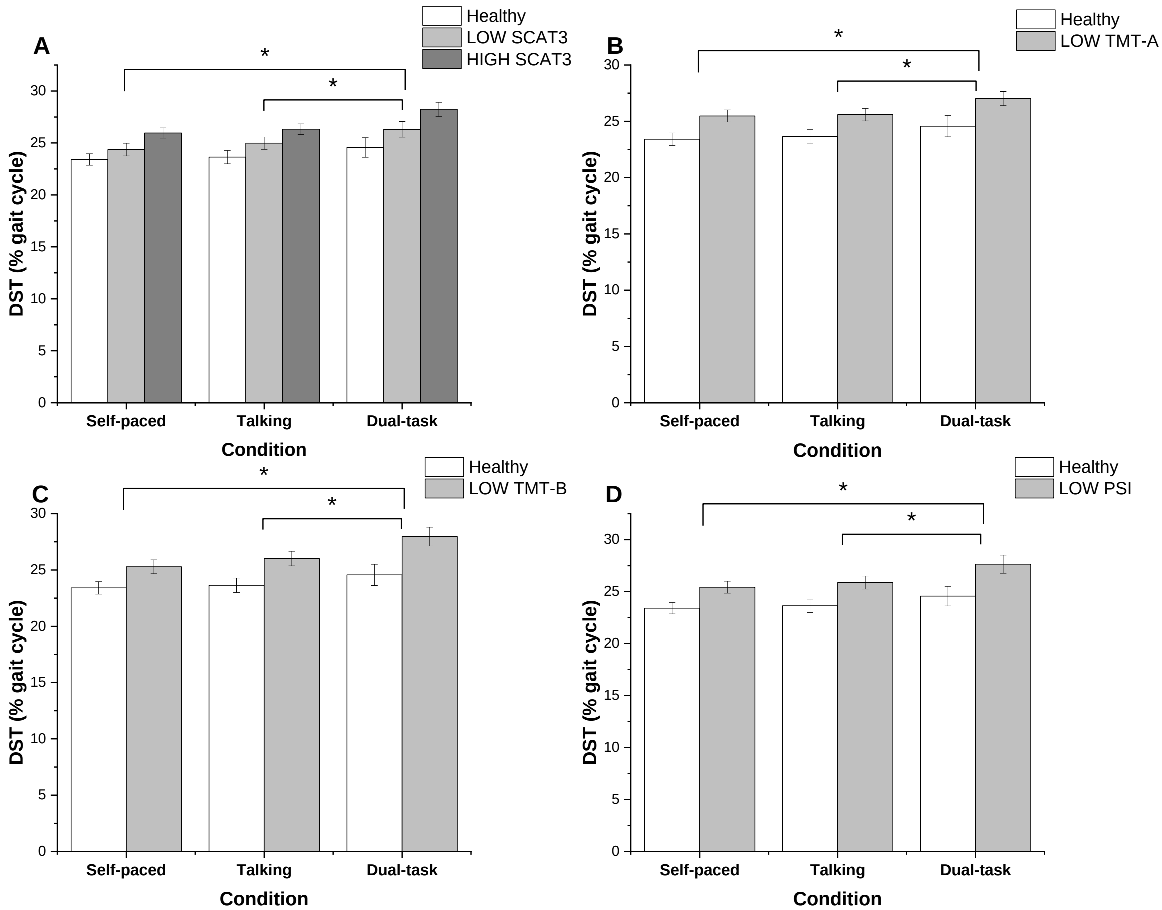

Figure 5. *Comparison of DST (% gait cycle) means across Self-paced, Talking and Dual-task conditions between the Healthy and Concussion Groups Values are represented as means and SE. Statistically significant condition differences are denoted by *. A) Subdivision of the concussion by SCAT3 scores. B) Subdivision of the Concussion Group by TMT-A scores. C) Subdivision of the Concussion Group by TMT-B scores. D) Subdivision of the Concussion Group by PSI scores.*

2.5 Discussion

The purpose of this study was to investigate the relationship between gait and cognition by examining cautious gait behaviour in community-dwelling adults with concussion. Overall, this study indicates that individuals with concussion display more cautious gait behaviour than sex and age matched healthy controls acutely after injury. This cautious gait behaviour was characterized by increased double support time and decreased cadence. Particularly, the results show that cautious gait behaviour is related to symptom severity and performance on neuropsychological tests of cognition. Individuals with concussion who performed below average on tests of processing speed and executive function had greater DST than the Healthy Group. This was similarly observed in individuals with high symptom severity scores. Increased cautious gait behaviour was observed during the Dual-task and may indicate deficits in cognitive domains such as attention, as the Dual-task is known to rely on effective division of attention.

2.5.1 DST and cadence: features of cautious gait behaviour

Gait velocity is a commonly used gait measure to assess different pathologies and there has been some evidence to show that it is abnormal in individuals with concussion compared to healthy controls (Fino et al., 2018). However, while a decreased gait velocity was observed in this study in the Concussion Group, it was not found to be statistically different than the Healthy Group. A decrease in gait velocity appeared to be a similar response in the Healthy and Concussion group in response to increased cognitive challenge. Gait velocity and double support time are thought to be related, wherein an increase in gait velocity results in a decrease in double support time and vice versa (Williams & Martin, 2019). However, such might not be the case in individuals with concussion. When examining the double support time of individuals with concussion with the same gait velocity as sex and age matched healthy controls, those with concussion had a higher double support time than their healthy match. This was observed across conditions, and even during the Max-paced condition, where individuals were instructed to walk their fastest (Appendix A). These results indicate that increases in double support time may occur due to factors other than gait velocity, such as cognitive functioning. While not considered cognitively impaired, individuals who performed below average on tests of executive function and processing speed had greater double support time and lower cadence than the Healthy Group. Velocity may therefore not be sensitive enough to the subtle deficits in cognition that can impact gait. However, considering that the ANOVA for velocity approached significance (p = .072), it is possible that that there was not enough power to detect a difference in velocity between groups due to the sample size.

The only gait measures that could differentiate between groups in the current study were DST and cadence. It is interesting that cadence showed consistent group effects along with DST in all the analyses. While cadence has not been characterized as a feature of cautious gait behaviour previously, the results of this study suggest that it is. Previous studies in older adults have found an association between processing speed and cadence (Martin et al., 2013; Verlinden et al., 2014). It has been suggested that the temporal component of cadence may be related to cognitive function, possibly due to the timing components of many neuropsychological assessments (Martin et al., 2013; Verlinden et al., 2014). While the rhythmic aspects of gait such as cadence are typically considered to be automatic and controlled by regions such as the brain stem and spinal cord, they may become more cortically mediated in response to injury, such as in the case of concussion (Morris et al., 2016).

2.5.2 Symptom severity impacts cautious gait behaviour

This study revealed group differences when comparing gait measures between healthy, LOW SCAT3, and HIGH SCAT3 individuals. These differences were observed for DST and cadence, whereby the HIGH SCAT3 group had a greater DST and lower cadence compared to the LOW SCAT3 group and the Healthy Group. The relationship between symptom severity and cautious gait behaviour in community-dwelling individuals with concussion can be explained by several factors. First, some of the symptoms assessed by the SCAT3 symptom scale can result in more cautious gait. For example, symptoms such as “balance problems”, “nausea or vomiting”, “drowsiness” may cause individuals to walk more carefully to maintain their stability during gait. Fatigue, both physical and mental, has been shown to cause increased DST during gait (Behrens et al., 2018; Dos Santos et al., 2019; Grobe et al., 2017). Mental fatigue, which could be related to the “mental fog” symptom assessed in the SCAT3 assessment, may be a reason for observed prolonged DST during the Dual-task which requires more attentional resources (Behrens et al., 2018). These findings suggest that other factors may contribute to cautious gait behaviour in addition to cognitive deficits.

2.5.3 Cautious gait behaviour increases with task difficulty

Double support time was higher and velocity, cadence, and step length were lower during the Dual-task compared to Self-paced condition. The addition of a cognitive task changed gait behaviour similarly between the Healthy and Concussion Group in all analyses; however, characteristics of cautious gait behaviour were more pronounced in the Concussion Group.

While the control group increased their cautious gait behaviour with increasing task challenge, cautious gait behaviour was higher in the Concussion Group across all three tasks. This implies individuals with concussion display cautious gait behaviour even during tasks with a low cognitive load. This implies that a task that may have been mostly automatic prior to injury, becomes more attention-demanding after concussion. In addition, despite scores on the cognitive tests used in this study being within normative values, the cautious gait behaviour observed during a low-cognitive task suggests that there may be subtle deficits in cognition which can impact normal walking and implies that there may be other factors that contribute to cautious gait behaviour. For example, immediately after injury, individuals with concussion may have a fear of falling which leads them to walk more cautiously during the Self-paced condition.

2.5.4 Cognitive load increases cautious gait behaviour

When assessing the effect of cognition on gait, this study revealed that individuals who score poorly on assessments of executive function and processing speed display more cautious gait behaviour than healthy controls. These differences were mainly observed for DST and cadence.

The majority of investigations of the relationship between gait and cognition have occurred in older adults. A review by Morris et al. that examined studies that investigated this relationship in older adults and populations with neurodegenerative diseases found that gait velocity has the strongest relationship with cognition (Morris et al., 2016). Although the present study did not carry out analyses of associations between gait and cognitive measures, our study found that gait speed was unable to differentiate between healthy individuals and those with concussion. It is important to note that the literature is dominated by studies that focus on gait velocity and so resultant reviews may be skewed.

Despite the differences in gait velocity between healthy controls and individuals with concussion shown in previous studies, it is important to highlight that these studies mostly comprise of athletes. This study examines gait behaviour in community-dwelling adults with concussion. Difference in pathology and population can contribute to differences in cognitive and gait abnormalities (Morris et al., 2016). While gait speed may be a common indicator of abnormal gait in athletes, our study shows that the same cannot be said in community-dwelling adults.

With the greatest cautious gait behaviour observed during the Dual-task, this suggests that individuals with concussion, though they are not considered cognitively impaired based on scores on the neuropsychological tests, may have subtle cognitive impairments that can only be detected by a challenging task like the Dual-task. The Concussion Group in each analysis made fewer responses than the Healthy Group during the Dual-task, which may imply that these individuals have a more difficult time dividing their attention between the cognitive and gait task and subsequently display a more pronounced cautious gait strategy than the Healthy Group.

The increased cautious gait behaviour observed in individuals with concussions could be reflective of several things. First, it implies difficulty in allocating appropriate attentional resources between the cognitive and gait task. The addition of a cognitive task during gait poses a greater threat to stability and requires a more pronounced cautious response than in healthy individuals. Indeed, the Concussion Group that scored more poorly on the test for executive function had greater characteristics of cautious gait. There are several neuropsychological models to explain information processing during a dual-task. A common theory is the capacity-sharing theory which suggests that the capacity of attentional resources is limited. As a result, the performance of two attention-demanding tasks causes at least one, or both tasks to deteriorate (Yogev-Seligmann et al., 2007). The change in performance of both the gait and cognitive task in the Concussion Group compared to the healthy controls suggests the attentional resource capacity in individuals with concussion may be more limited due to deficits in executive functions, processing speed, and attention. The increased cautious gait behaviour may also be due to cognitive-motor interference as executive functions and gait control may have shared neural networks in the brain (Li et al., 2018).

There is evidence from brain imaging studies that suggests the presence of white matter damage in the prefrontal cortex following concussion. Damage to this area is significant as the prefrontal cortex is involved in processes of executive functions that modulate gait (Koenraadt et al., 2014; Malouin et al., 2003). The importance of the prefrontal cortex in gait has been shown in clinical populations such as Parkinson's (Morris et al., 2016). In the prefrontal cortex, acetylcholine is important for cognitive function, specifically for attentional processes (Yarnall et al., 2011). In Parkinson's, cholinergic dysfunction is associated with disturbances in gait (Rochester et al., 2012). Evidence from animal and human studies suggests that cognitive deficits in TBI may results from post-injury cholinergic dysfunction (Arciniegas, 2003). The overproduction of acetylcholine, along with other neurotransmitters, that occurs acutely after TBI may contribute to impairments in cognitive functions such as attention (Arciniegas, 2003; Saija et al., 1988). While the effect of cholinergic dysfunction on gait in TBI has yet to be investigated, evidence from other studies reveals an association between gait and cholinergic function, with strong associations between gait velocity and acetylcholine levels. In addition, cholinergic activity has been found to be associated with Dual-task gait (Kelly et al., 2012; Pelosin et al., 2016). This suggests that acetylcholine may affect gait indirectly through cognition. Finally, poor gait performance was only found to be associated with acetylcholine in the neocortex, responsible for higher order functions such as cognition (Bohnen et al., 2012); this provides further support for the role of cognition in gait.

The activation of executive-attention networks via cortical networks is employed to alter postural control (Morris et al., 2016). Alterations in these networks and deficits in executive function and attention in concussion can result in poorer postural control (Kelly et al., 2012; Lord et al., 2013; Martin et al., 2013). During gait, double support is the most stable part of the cycle, and therefore increased double support may be a compensatory strategy to increase stability in response to decreased postural control due to deficits in executive function and attention.

2.5.5 Limitations and future studies

Control participants did not complete the SCAT3 symptom assessment or any of the neuropsychological assessments, limiting the ability to compare symptom and cognitive profiles between the concussion and control groups. Additionally, no specific cognitive test of attention was used, making it difficult to draw conclusions about the relationship between attention and cautious gait behaviour.

Future studies can incorporate a more challenging cognitive task during dual-task gait. Specifically, the addition of a cognitive task targeted at a specific cognitive domain may be more informative regarding the relationship between gait and specific cognitive domains. For example, participants can complete a test such as the Paced Auditory Serial Addition Test (PASAT), which primarily assesses attention, while walking.

2.6 Conclusion

In conclusion, this study found that cautious gait behaviour is more pronounced in individuals with concussion compared to healthy controls. More cautious gait behaviour was present during the Dual-task, though the Concussion Group had more cautious gait behaviour than the Healthy Group in each of the gait tasks. In the Concussion Group, cautious gait behaviour was influenced by symptom severity and poor cognitive function in the executive function and processing speed domains. It is important to note that in this study, gait velocity was not able to statistically detect differences between the Healthy Group and individuals with concussion, despite being an important determinant of functional gait. Double support time and cadence, however, were able to differentiate between the groups and therefore may be more effective at detecting gait and cognitive changes following concussion.

These results have significant implications. First, the presence of increased cautious gait behaviour and decreased number of responses during the Dual-task imply subtle cognitive deficits that may not be detected by commonly administered neuropsychological tests. In the absence of cognitive deficits characterized by commonly administered clinical assessments, the presence of cautious gait behaviour may be used by clinicians as an indicator of cognitive issues in individuals with concussion. Second, the increased cautious gait behaviour seen in individuals with concussion has implications for safety. If the cautious gait behaviour displayed by the Healthy Group is considered the optimal amount in response to cognitive challenge, the Concussion Group's cautious gait behaviour then falls outside of this range and may be considered unsafe, making concussed individuals more vulnerable to perturbations and falls.

Clinicians can target gait rehabilitation towards addressing cautious gait behaviour using a dual-task approach to ensure patients return to healthy levels and are able to interact with their everyday environment safely.

Chapter 3: Characterization of recovery of cautious gait behaviour after concussion

3.1 Abstract

Previous research in athletes has identified that cautious gait behaviour may persist past perceived concussion recovery. What recovery of cautious gait behaviour looks like in community-dwelling adults with concussion has yet to be investigated. Therefore, the purpose of this study is to characterize the recovery of cautious gait behaviour in this population over 12 weeks. To do so, responsiveness and minimal detectable change (MDC) of spatiotemporal gait measures (velocity, double-support time, cadence, step length) were assessed for each of the gait tasks (Self-paced, Talking, and Dual-task). Symptom severity, cognitive function, and age were then assessed as predictors for recovery. Results revealed that gait measures were most responsive to change during the Dual-task. MDC_{95} values increased from the Self-paced to Dual-task condition for double support time and cadence but were similar across conditions for gait velocity and step length. Cautious gait behaviour did not recover in over half of the sample in all tasks. No logistic regression models were significant in discriminating between Recovered and Not Recovered individuals. A one unit increase in SCAT3 change score was associated with a 1.035 odds of recovering in Self-paced double support time (p = .011), and the odds of recovering in Dual-task cadence were 1.073 higher for a one unit increase in PSI change score (p = .029), holding all other variables constant. According to these results, the Dual-task may be a strong candidate for clinical use in monitoring the effects of concussion in community-dwelling adults over time.

3.2 Introduction

A concussion is a traumatic brain injury that can result in a wide variety of symptoms including somatic, cognitive, and physical changes. In Ontario, the mean incidence of concussion is 1153 per 100 000 residents in a year, with the majority of these injuries occurring in community-dwelling adults (Langer et al., 2020). Due to its importance in daily activities, the impact of concussion on gait has been widely studied. However, most of this research focuses on athletes with concussion, despite the importance of gait for functional and safe living in community-dwelling individuals. In addition, differences in populations, gait measures, and tasks across studies have resulted in mixed findings (Fino et al., 2018). This makes it difficult to generalize these results to community-dwelling adults and translate the findings for use in clinical settings.

Because activities of daily living can be diverse and complex, the use of a simple gait task such as self-paced walking to assess the impact of concussion on gait may not be suitable. Instead, to better reflect the involvement of cognition in gait, dual-tasks which involve walking while performing a simultaneous cognitive task can be better experimental assessments of gait impairments following concussion. The dual-task may also be useful for identifying cognitive deficits as it relies on cognitive domains such as executive function to facilitate the performance of two simultaneous tasks (Yogev-Seligmann et al., 2007).

One way to understand the relationship between gait and cognition following concussion is by examining how concussion can result in cautious gait behaviour. Cautious gait behaviour is an ambulation strategy typically observed in older adults which is commonly characterized by a decreased gait speed, increased double support time (DST), and a widening of the base of support. This strategy is observed in healthy individuals during instances of divided attention and may be a response meant to increase stability (Crowley et al., 2019). However, in clinical populations, overly cautious gait behaviour may pose a risk to safety and increase risk of falls (Pirker & Katzenschlager, 2017). Factors such as cognitive impairments, balance deficits, and fear of falling can lead to cautious gait behaviour. And, since these problems can arise after concussion, it is likely that changes in DST occur in parallel.

Only two previous studies have characterized cautious gait behaviour in individuals with concussion. Both studies examined individuals with a history of concussion. Buckley et al. specifically investigated the effect of multiple concussions on single-task gait. They found increased double support time in individuals with a history of 1-3 concussions in comparison to healthy controls (Buckley et al., 2016). However, the study investigated college aged student athletes. Martini & Broglio showed similar results in a population of university students using single and dual-tasks; however, history of concussion was self-reported and injury severity was not graded (Martini & Broglio, 2018). In addition, the mean time post-injury was 6.3 years. The length of time since injury and the use of self-report make it difficult to attribute the gait changes observed to concussion as symptoms and balance impairments are reported to resolve within 5-7 days in this population (Macciocchi et al., 1996; McCrea et al., 2003). Additionally, because these studies were not longitudinal, conclusions about recovery of cautious gait behaviour cannot be made. It is also noteworthy that the results of these studies may not be generalizable to community-dwelling adults with concussion. Previous research into recovery of balance in community dwelling adults with concussion shows that recovery timelines in this cohort are different to those observed in collegiate athletes (McCrea et al., 2003; Sweeny et al., 2020).

In order to understand how cautious gait behaviour changes over time after injury, it is important to assess the capability of different conditions to detect change (responsiveness) in gait measures characteristic of this gait pattern. Additionally, to interpret changes in cautious gait behaviour, the true change in gait measures over time must be evaluated using indices such as Minimal Detectable Change (MDC). However, these properties have yet to be established in individuals with concussion. In addition, it is also important to understand what predictors contribute to recovery. Poor cognitive functioning in areas of executive function and processing speed is associated with gait changes such as decreased gait velocity (Martin et al., 2013). Symptoms evaluated in the SCAT3 such as balance problems, drowsiness, and dizziness may also impact gait (Hunt et al., 2021; Wood et al., 2019). Age may also impact the presence and recovery of cautious gait behaviour, as a decrease in gait velocity and increase in double support time are common in healthy older adults (LaRoche et al., 2014). In addition, based on previous work in this thesis that identified higher levels of cautious gait behaviour in individuals with poorer scores on neuropsychological assessments and those with higher symptom severity, it is possible that these factors may predict recovery.

The purpose of this study is to characterize recovery of cautious gait behaviour in community-dwelling adults with concussion. This study will also aim to assess the sensitivity of gait measures and conditions to detect change, as well as identify values of true change over time to characterize whether individuals have recovered 12 weeks after concussion. A change in cautious gait behaviour may be indicative of recovery. For example, an initial elevation and gradual decline in cautious gait behaviour may indicate cognitive and gait impairments after concussion that recover over time. In contrast, absence of change may suggest that recovery of cautious gait behaviour does not occur 12 weeks post-concussion or that it was not affected by concussion to begin with. Based on results from Chapter 2, it is hypothesized that Dual-task double support time and cadence will be most responsive to change over 12 weeks. Due to the role of executive function, processing speed, and symptom severity on cautious gait behaviour, it is expected that change scores in these factors will predict recovery. Specifically, executive function and processing speed will predict recovery of double support time and cadence in the Dual-task.

3.3 Methods

Data used in this study were collected at the Hull-Ellis Concussion and Research Clinic at the Toronto Rehabilitation Institute. Individuals with concussion were referred from 5 partnering emergency departments in Toronto and data collection occurred from February 2016 to September 2019. Healthy control data were also collected. Patients were assessed within the first 7 days of injury to mark Week 1 and were subsequently re-assessed at Weeks 2, 4, 8, 12, and 16 post injury. Participants in either group were excluded if they were missing gait data at Week 1, 2, or 12.

The following demographic data were collected for the Concussion and Healthy Group: age, sex, height, previous health conditions, and years of education. Additional information collected for the Concussion Group included: weight, history of previous concussion, prior mental health conditions, time to first appointment after injury, and prior migraine headaches. Exclusion and inclusion criteria for the Concussion Group are listed in Table 10. Healthy controls were excluded if they had a history of concussion or other neurological conditions, musculoskeletal injuries, or vestibular disorders within one year of assessment that may affect gait. Because weight data was not collected for the Healthy Group, it was assumed that the participants had a BMI lower than 30.

Table 10. *Inclusion and exclusion criteria for the Concussion Group.*

Inclusion criteria	Exclusion criteria
• 17-85 years of age • Diagnosed with a concussion by an ED physician • Glasgow Coma Score of 13-15 • No focal neurological findings or positive neuroimaging finding (or imaging was deemed unnecessary on CT scan decision rules in ED) • Participant is willing to come to first appointment within 7 days of injury • Sufficient proficiency in English to be able to complete questionnaires and tools used in study i.e. Grade 6 or above reading level	• Community physician referrals • Injury occurred greater than seven days to first Hull-Ellis physician-assessment • Injury occurred as the result of a work-place injury or motor-vehicle collision (MVC) • Positive image or Neurological findings • Symptomatic from a previous concussion in the last three months or less • In-patient admission • Ongoing or history of MSK injury within one year of assessment* • BMI > 29.9

**previous joint replacement surgery, previous orthopaedic surgery, previous lower limb condition/injury (causing muscle or joint discomfort or reduced range of motion), or previous back pain/injury*

3.3.1 Assessments

A pressure-sensitive gait mat (GaitRite, CIR Systems Inc, Havertown, PA) was used to collect gait data. Participants walked across the mat in three different conditions. A minimum of 16 footfalls was required in each condition. In the Self-paced condition, participants were required to walk across the mat at a self-selected speed. In the Talking condition, participants walked across the mat at a self-selected speed while counting upwards by one from a three-digit number. The Dual-task condition required participants to walk across the mat at a self-selected speed while counting backwards by seven from a three-digit number (Manning, 1982). Measures of interest included velocity (cm/s), cadence (steps/min), step length (cm), and double support time (% gait cycle). Velocity and step length were normalized to participant height as leg length information was not collected.

The Concussion Group completed the Concussion Assessment Tool Edition 3 (SCAT3) (Guskiewicz et al., 2013), which required patients to self-report symptom severity on 22 symptoms using the Symptom Severity Subscale. Each symptom could be rated from 0 (none) to 5-6 (severe), for a maximum possible score of 132.

The Concussion Group also completed two neuropsychological tests to assess cognition at Week 1, 2, and 12. The Trail Making Test Part B was used to assess executive function, and was corrected for age, sex, and education level. Executive function is a set of cognitive skills that include cognitive flexibility and attention that are necessary to plan, monitor and execute goal-directed complex actions (Sira & Mateer, 2014). Because variations in gait during motor-cognitive dual-tasks rely on executive processes, and performance during these activities requires the ability to effectively allocate attention between tasks that are done simultaneously, executive function was chosen as a cognitive domain of interest (Allali et al., 2008). The Trail Making Test Part A and the Coding and Symbol search subtests from the WAIS-IV were used to assess processing speed (Lichtenberger et al., 2012). The Trail Making Test Parts A was corrected for age, sex, and education level. The Coding and Symbol search subtests were corrected for age and combined into a composite score called the Processing Speed Index (PSI) (Weiss et al., 2019). Processing speed is the rate at which information is processed and responded to, and it is linked to the capacity to employ other cognitive abilities efficiently (Drozdick et al., 2013). Processing speed is critical in the motor-cognitive dual-tasks for both completing the cognitive task while walking and performing executive functions such as division of attention.

3.3.2 Statistical Analysis

All statistical analyses were completed using SPSS v28 (IBM, Armonk USA). Statistical significance was set at p = .05. The following analyses were carried out:

Responsiveness. To assess the sensitivity of the gait measures to detect change, the Standard Response Mean (SRM) was calculated to measure responsiveness. The SRM is an effect size calculated by dividing the average difference between two time points by the standard deviation of that difference (Middel & Van Sonderen, 2002). Because the data analyzed in this study is paired, the corrected SRM was used (Middel & Van Sonderen, 2002). The corrected SRM is calculated by taking into account the correlation (r) between the two time points and is calculated as follows:

$$Corrected\ SRM = SRM\ \times \sqrt{2}\ \times \sqrt{(1-r)}$$

The corrected SRM can then be interpreted using Cohen's thresholds, where a value less than 0.5 is considered to be a small effect size, 0.5 to 0.8 is interpreted as moderate, and greater than 0.8 is considered large (Middel & Van Sonderen, 2002).

Minimal detectable change. To assess whether changes in gait measures from Week 1 to 12 were true changes not due to error, calculations of Minimal Detectable Change values for each of the gait measures at each condition were calculated as follows:

$$MDC_{95} = 1.96 \times SEM \times \sqrt{2}$$

Where,

$$Standard\ error\ of\ measurment\ (SEM) = SD\ (first\ test) \times \sqrt{(1 - ICC)}$$

The intraclass correlation coefficient (ICC) is a measure of reliability that can be used to assess the test-retest reliability of a measure (Koo & Li, 2016). It assesses the degree to which scores obtained from a measure can remain consistent over a short time (Koo & Li, 2016). For this analysis, a two-way mixed-effects model with absolute agreement was used to calculate ICC (Koo & Li, 2016). Because ICC analysis requires a short time interval between the two tests (typically 7-14 days) and stability between those tests in terms of scores, individuals with concussion who remained stable in their gait measure scores between Weeks 1 and 2 were used to calculate ICC. To define a criterion for stability, the 95% CI of the changes between Weeks 1 and 2 for the Healthy Group was calculated for each gait measure. Individuals in the Concussion Group whose changes were within that 95% CI were then used for the ICC analysis.

Classification of recovery. To assess whether cautious gait behaviour in the Concussion Group recovered at Week 12 post-injury, a criterion for recovery was developed. Recovery in each gait measure at each condition required participants to meet the following two conditions:

I. The change score between Week 1 and 12 must be greater than the MDC_{95}.

II. Gait values at Week 12 must be above or below the lower or upper bounds of the 95% CI for the Healthy Group for that gait measure, respectively, depending on the gait measure.

Participants were classified as Recovered or Not Recovered.

Predictors of recovery. To test the hypothesis that cognitive function and symptom severity predict recovery, binomial logistic regressions were performed for each of the gait measures in each of the conditions. The potential predictors were selected a priori based on previous literature and findings from Chapter 2, and thus they were retained in the model regardless of the numerical value of their *p* values. For each regression, TMT-B, PSI, and SCAT3 change scores (Week 12 – Week 1), and Age were entered into the model. While the TMT-A and PSI are both scores of processing speed, PSI was pre-selected as a predictor because the Coding and Symbol Search subtests are more comprehensive tests of processing speed and assess other cognitive functions such as attention (Flanagan & Kaufman, 2004).

Before performing the binary logistic regressions, the assumptions of the regression were verified. The Box-Tidwell approach was used to confirm the linear relationship between the continuous independent variables and the logit transformation of the dependent variable. Multicollinearity of the predictors was assessed using Tolerance/VIF values. The casewise diagnostics output of the binary logistic regression procedure on SPSS was used to check for outliers. Cook's and leverage values were used to check influential and leverage points.

3.4 Results

3.4.1 Participant characteristics

In total, 83 participants with concussion were eligible to be included in this study. The Concussion and Healthy Group participant characteristics are summarized in Table 11.

Table 11. *Demographic information for the Concussion and Healthy Group.*

Variable		Concussion (n=83)	Healthy (n=15)
Age [Mean (SD)]		34.9 (13.3)	31.3 (11.2)
Sex [Number (%)]			
	Males	24 (28.9)	6 (40)
	Females	59 (71.1)	9 (60)
Education level			
	Less than high school diploma	0	0
	High school diploma	7	1
	Incomplete postsecondary studies	5	0
	Trade certificate/diploma or College, CEGEP, or other non-university certificate/diploma	9	3
	Bachelor's degree	46	3
	Master's degree	15	8
	PhD	1	0

The Healthy Group's means and 95% confidence intervals for all great measures are presented in Table 12. In the Concussion Group, preliminary results showed a reduction in double support time and an increase in velocity, cadence and step length at Week 12 compared to Week 1. In each condition, means for double support time, velocity and cadence fell outside of the 95% CI of the Healthy Group at Week 1, but were within the healthy 95% CI at Week 12.

Scatter plots for the gait measures across the different conditions at Week 1 and 12 are presented in Figure 6 for the Concussion Group.

Table 12. *Gait means across conditions for the Healthy Group, including the 95% confidence interval (CI).*

	Condition	Mean (SD)	95% CI
	Self-paced	23.4 (2.1)	[22.2, 24.6]
DST	Talking	23.6 (2.5)	[22.3, 25.0]
	Dual-task	24.6 (3.6)	[22.6, 26.6]
	Self-paced	0.73 (0.11)	[0.67, 0.79]
Velocity	Talking	0.72 (0.11)	[0.66, 0.78]
	Dual-task	0.67 (0.12)	[0.61, 0.74]
	Self-paced	112.4 (6.4)	[108.8, 115.9]
Cadence	Talking	111.7 (7.3)	[107.7, 115.8]
	Dual-task	108.2 (9.3)	[103.1, 113.4]
	Self-paced	38.9 (4.2)	[36.5, 41.2]
Step length	Talking	38.2 (4.6)	[35.7, 40.8]
	Dual-task	36.8 (4.8)	[34.2, 39.5]

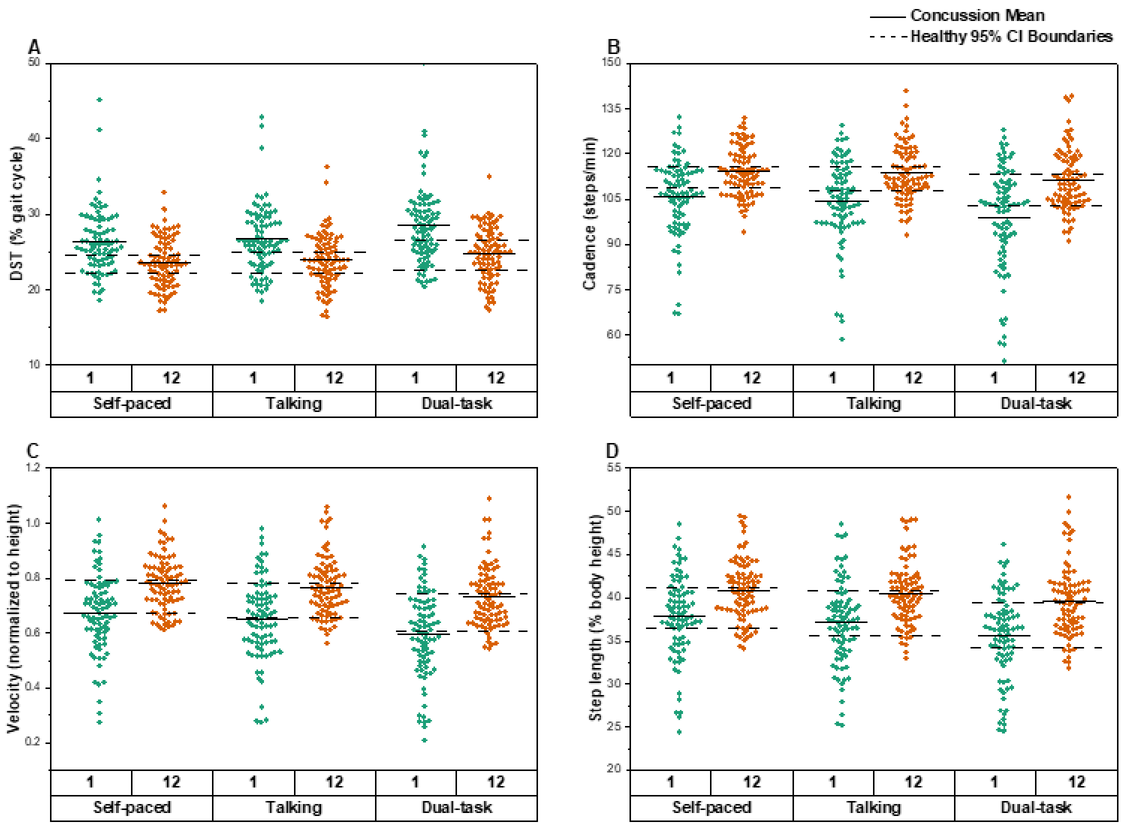

Figure 6. *Scatter plots of gait measures in the Self-paced, Talking, and Dual-task conditions at Week 1 and 12. A) DST (% gait cycle). B) Cadence (steps/minute). C) Velocity (cm/s normalized to body height). D) Step length (% body height).*

3.4.2 Responsiveness

Assessment of responsiveness found all gait measures to be responsive to change, with measures being the most responsive during the Dual-task condition. Corrected SRM values for each gait measure are summarized in Table 13. With regards to gait measures during the Dual-task, velocity was the most responsive, followed by double support time, cadence, and step length. However, all gait measures are considered to have large effect sizes during the Dual-task according to Cohen's thresholds.

Table 13. Corrected SRM values for each gait measure across conditions.

Condition	Corrected SRM			
	DST	Velocity	Cadence	Step Length
Self-paced	0.777	0.883	0.768	0.696
Talking	0.801	0.906	0.761	0.701
Dual-task	0.904	0.984	0.822	0.806

3.4.3 Minimal detectable change

Table 14 presents the MDC_{95} values for each gait measure across conditions. MDC_{95} values were only applied to individuals with complete gait and cognitive data (n = 74). Individuals with missing data were excluded.

Table 14. *MDC_{95} values for each gait measure across conditions. The number of individuals exceeding the MDC_{95} at Week 12 is included as a percentage.*

Condition	DST (% gait cycle)		Velocity (cm/s normalized to height)		Cadence (steps/min)		Step Length (% height)	
	MDC_{95}	% Exceeding MDC_{95}	MDC_{95}	% Exceeding MDC_{95}	MDC_{95}	% Exceeding MDC_{95}	MDC_{95}	% Exceeding MDC_{95}
Self-paced	2.5	50.0	0.12	44.5	8.9	41.9	3.3	45.9
Talking	2.8	50.0	0.10	45.9	7.6	45.9	2.5	55.4
Dual-task	4.0	39.2	0.12	48.6	11.1	40.5	3.2	58.1

3.4.4 Classification of recovery

In addition to exceeding the MDC_{95}, recovery within a gait measure and condition required participants at Week 12 to be below the upper limit of the healthy 95% CI for DST, or above the lower limit of the healthy 95% CI for velocity, cadence, and step length. Only participants with complete gait and cognitive data were included (n = 74). The greatest proportion of Recovered individuals was observed in the Dual-task condition for step length (52.7%). DST and cadence had the greatest proportions of individuals who did not recover in the Dual-task compared to the other gait measures. The number of individuals who were classified as Recovered or Not Recovered is summarized in Table 15.

Table 15. *The proportion of individuals (%) at Week 12 who were classified as Recovered or Not Recovered according to MDC_{95} values and the 95% CI of the Healthy Group.*

	Condition	Recovered	Not Recovered
DST	Self-paced	39.2	60.8
	Talking	37.8	62.2
	Dual-task	35.1	64.9
Velocity	Self-paced	36.5	63.5
	Talking	40.5	59.5
	Dual-task	47.3	52.7
Cadence	Self-paced	31.1	68.9
	Talking	36.5	63.5
	Dual-task	33.8	66.2
Step length	Self-paced	41.9	58.1
	Talking	51.4	48.7
	Dual-task	52.7	47.3

3.4.5 Predictors of recovery

Nine individuals were excluded due to missing cognitive data (n = 74). Table 16 presents the SCAT3, TMT-B, and PSI values at Week 1 and 12, as well as the change scores from Week 1 to 12. Change scores were calculated as Week 12 – Week 1 values. Mean scores for the TMT-B and PSI in the Concussion Group in each week are within normative reference values (Psychcorp, 2020; Tombaugh, 2004).

Table 16. *Mean values of SCAT3, PSI, and TMT-B at Week 1 and 12. Change scores between Week 1 and 12 are also included. Values are presented as mean (SD).*

Predictor	**Week 1**	**Week 12**	**Change Score**
SCAT3 Symptom Severity Subscale* total score	41.8 (23.6)	12.1 (17.6)	−29.7 (20.9)
Processing Speed Index	106.3 (10.1)	118.4 (11.6)	12.1 (8.9)
TMT-B T-Score	48.9 (9.5)	56.0 (10.9)	7.1 (8.2)

**In the logistic regression analysis, change scores were calculated as Week 1 – Week 12 for SCAT3 to maintain positive values for assessment of linearity.*

Assumptions of binary logistic regressions

Linearity of the continuous variables with respect to the logit of the dependent variable was assessed via the Box-Tidwell (1962) procedure. A Bonferroni correction was applied using all ten terms in the model resulting in statistical significance being accepted when $p < .005$ (Tabachnick & Fidell, 2014). Based on this assessment, all continuous independent variables were found to be linearly related to the logit of the dependent variable. There was no evidence of multicollinearity, as all tolerance values were greater than 0.1. There were no outliers, no leverage values greater than 0.2, and no values for Cook's distance above 1. Tables associated with the assumptions of the logistic regression are presented in Appendix B.

Binary logistic regressions

No regression models were significant (Table 17). While the overall model was not statistically significant, SCAT3 change score was a significant predictor of recovery of double support time in the Self-paced condition (p = .011, OR = 1.035, 95% CI [1.008, 1.063]), and PSI change score was a significant predictor of recovery of Dual-task cadence in (p = .029, OR = 1.073, 95% CI [1.007, 1.142]).

Table 17. *Binomial logistic regression statistics for each gait measure in each condition. Included are Chi-square, significance, and Nagelkerke R^2 values.*

Variable	**Self-paced**			**Talking**			**Dual-task**		
	$\chi 2$	p	R^2	$\chi 2$	p	R^2	$\chi 2$	p	R^2
DST	7.725	.102	.134	2.751	.600	.05	7.894	.096	.141
Velocity	1.337	.855	.025	1.571	.814	.028	.939	.919	.017
Cadence	3.273	.513	.061	.993	.991	.018	6.368	.173	.114
Step length	6.016	.198	.105	2.992	.559	.053	2.156	.707	.038

3.5 Discussion

The purpose of this study was to characterize the recovery of cautious gait behaviour in community-dwelling adults with concussion. Results of this study indicate that gait measures are most responsive to change in the Dual-task. Recovery across gait measures varied, with the lowest proportion of recovery for double support time and cadence. Symptom severity was only a predictor of recovery for Self-paced double support time and PSI was only a predictor for Dual-task cadence; no other variables were found to be significant predictors. These results show that recovery of cautious gait behaviour, characterized by double support time and cadence, occurred in less than 40% of the participants across conditions at Week 12 post-concussion.

3.5.1 Dual-task elicits the highest level of responsiveness

As hypothesized, the Dual-task was the condition that elicited the highest level of responsiveness over 12 weeks for all gait measures investigated in this study, as seen by SRM values evaluated with a large effect size. Responsiveness for double support time and cadence was lower in the Self-paced and Talking conditions. These conditions may not be challenging enough to see changes in cautious gait behaviour over time. In the absence of pre-injury baseline values, which is a common case in community-dwelling adults, it can be difficult to determine the presence and level of impairment in areas such as gait, especially if normative values are not available. Results from Chapter 2 suggest that there is greater cautious gait behaviour in the Dual-task compared to Self-paced and Talking tasks. Combined with results from this study that identify the Dual-task as a task better able to distinguish real change over time, the Dual-task may be a more comprehensive and sensitive way of detecting persisting gait abnormalities after concussion. While the responsiveness of gait conditions has not previously been established in the concussion literature, there are studies that highlight the difference between single and dual-task conditions. For example, Berkner et al. found that differences in gait velocity and cadence between concussion participants and healthy controls lasted longer in the dual-task condition compared to single-task (Berkner et al., 2017). Another study that assessed dual-task tandem gait found similar results (Howell et al., 2013). Assessments that employ self-paced walking may overlook impairments that persist and may not be responsive enough to detect change that occurs due to recovery or treatment.

To my knowledge, this is the first study that has assessed the responsiveness of gait measures across different conditions in concussion. Choosing an assessment tool requires evaluation of the tool's psychometric properties, especially when assessing change over time due to disease progression or improvements due to interventions (Guyatt et al., 1987). Therefore, it is important that the scores of the assessment chosen have the potential for change. It is equally as important to choose an assessment that can capture the relevant skills that reflect the outcome. In the case of assessing changes in cautious gait behaviour over time, the results from this study indicate that gait scores in the Dual-task not only have the potential for change but are also challenging enough to reflect skills required in everyday activities that are of interest to clinicians and patients when managing the effects of concussion (McCulloch, 2007).

3.5.2 Predictors of recovery

Overall, SCAT3, TMT-B, PSI, and Age were not predictors of recovery for any of the gait measures in any of the conditions, with the exception of Self-paced double support time and Dual-task cadence. A major limitation of this analysis that likely contributed to the results is the small sample size. Small sample sizes in logistic regression can impact the development of accurate models and may limit the ability to adequately represent the cases (van Smeden et al., 2019).

PSI change score was a predictor of recovery for Dual-task cadence, where individuals who had greater improvements in PSI score from Week 1 to 12 were more likely to fall into the Recovered outcome. Previous findings from Chapter 2 indicated that individuals with poor processing speed had a lower cadence than healthy controls. It follows then that an improvement in processing speed is associated with an increased likelihood of cadence recovering. This effect was not present in the Self-paced and Talking tasks for several reasons. First, the responsiveness of the Self-paced and Talking tasks is evaluated as having a medium effect size, whereas the Dual-task has a large effect size. Second, because performance in dual-task conditions relies partly on processing speed, it can detect impairments in this task more readily than less challenging tasks. Specifically, the temporal component of cadence may be related to processing speed function and therefore PSI can predict recovery of this gait measure in the Dual-task (Martin et al., 2013; Verlinden et al., 2014).

It was hypothesized that predictors of recovery would vary by condition. However, cognitive change scores did not predict recovery in any gait measures in the Dual-task condition with the exception of cadence. Several reasons may have contributed to this observation. First, cognitive performance in the Concussion Group did not significantly differ between Week 1 and 12, and therefore the change scores were low and likely did not differ between individuals who recovered and those who did not for most gait measures. Second, cognitive scores at Week 1 and 12 fell within normative ranges. While this suggests that perhaps the Concussion Group was not cognitively impaired, it may be that the cognitive tests used were not sensitive enough to assess potentially subtle deficits and their recovery. Instead, performance on the Dual-task may better reflect these deficits. Third, there are limitations to the sensitivity of traditional concussion assessments such as neuropsychological tests. The presence of cautious gait behaviour despite normative cognitive scores implies that there are subtle cognitive deficits that are unidentifiable by cognitive tests. In addition, the use of these tests to infer real world functioning may pose an issue with regards to ecological validity (Chaytor & Schmitter-Edgecombe, 2003). Ecological validity refers to the degree to which results acquired in controlled experimental conditions are comparable to those obtained in a real-world environment. Many neuropsychological tests only have a moderate level of ecological validity and may not be reflective of cognitive deficits and their effects on individuals outside of the testing environment (Chaytor & Schmitter-Edgecombe, 2003).

3.5.3 Cautious gait behaviour is still present 12 weeks post-concussion

Across conditions, less than 40% of the participants in this study were classified as Recovered for double support time and cadence. Though this study only looked at 12 weeks post-injury, the persisting cautious gait behaviour is in line with previous studies that have identified cautious gait behaviour in individuals with concussion for up to six years post-injury (Buckley et al., 2016; Martini & Broglio, 2018). This finding has significant implications for safety after concussion, as well as for the treatment of this injury. First, this finding suggests that while traditional assessments of concussion may indicate concussion recovery, subtle impairments in cognition and gait may persist for up to 12 weeks or longer. Evaluation of cautious gait behaviour may then be a novel way to assess concussion recovery and the effectiveness of interventions. Second, treatment can target cautious gait behaviour. Specifically, dual-task training may be effective at targeting subtle cognitive and gait impairments and reducing cautious gait behaviour (McCulloch, 2007).

Because one of the criteria for being characterized as Recovered for a gait measure was to fall above/below the Healthy Group's 95% CI for that measure, the individuals who did not recover can be said to have a level of cautious gait behaviour that is outside of healthy bounds and may affect safety and performance. One way cautious gait behaviour may compromise safety and performance is by increasing the risk of falls. In older adults, characteristics of cautious gait behaviour have been identified as risk factors for falls (Gschwind et al., 2010; Kwon et al., 2018; Mak, Young, Chan, et al., 2020). The presence of cautious gait behaviour in the Dual-task suggests that cognitive deficits may persist for months after injury. These potential deficits in attention, processing speed, and executive function may make it difficult to confront and adapt to challenges during gait such as obstacles and thus increase the risk of falls (Ambrose et al., 2013). In addition, while the risk of lower body injuries after concussion has only been investigated in athletes, it is possible that cautious gait behaviour may contribute to an increased risk of sustaining a lower body injury after concussion in community-dwelling adults.

3.5.4 Limitations and future studies

A major limitation of the regression analyses in this study is the small sample size. Logistic regressions require a ratio of 10:1 of events:non-events to the number of predictors. Given this, the sample size in the present study is too small and therefore makes it difficult to differentiate between individuals who recovered and those who did not. Another limitation concerns the characterization of recovery. There were participants whose gait change scores were less than the MDC_{95} and who were within healthy boundaries. These individuals were characterized as Not Recovered as outlined in the criteria for recovery, but it is possible concussion did not affect their gait. However, the lack of baseline data makes it difficult to truly determine whether these individuals were not impaired to begin with or whether 12 weeks was not sufficient to see recovery. The lack of baseline values also limits the ability to assess whether individuals returned to pre-injury function.

Future studies can incorporate larger sample sizes to assess predictors of recovery of cautious gait behaviour. Additionally, future work should examine whether cautious gait behaviour increases risk of falls by utilizing more complex gait tasks that assess obstacle navigation and using conditions which expose participants to perturbations.

3.6 Conclusion

Results from this study indicate that cautious gait behaviour did not improve in more than half of the sample. This study does not support the hypothesis that SCAT3, TMT-B, PSI, and Age predict recovery of cautious gait behaviour in individuals with concussion. Responsiveness and MDC values of the measures were greatest in the Dual-task condition. In addition, recovery of cautious gait behaviour was lowest in the Dual-task. Together, these findings imply that gait measures in the Dual-task may be more sensitive at detecting subtle cognitive deficits that may go undetected with typical neuropsychological assessments, as well as more sensitively identify recovery of gait and cognition following concussion.

Despite symptom resolution and normative cognitive performance at Week 12 post-concussion, cautious gait behaviour was still present in over half of the sample. The results of this study emphasize that impairments in gait and cognition may persist for months after concussion and may not be detected by traditional concussion assessments. Concussion evaluations should include gait assessments as part of concussion management to better inform recovery and decisions with regards to return to life activities.

Chapter 4: General Discussion

The focus of this thesis was to investigate the relationship between gait and cognition in community-dwelling adults with concussion by characterizing cautious gait behaviour. In Chapter 2, the presence of cautious gait behaviour acutely after concussion was determined and the effects of cognition and symptom severity were examined. Cautious gait behaviour, characterized by increased double support time and lower cadence, was affected by increasing task challenge as well as poorer symptom severity and performance on tests of executive function and processing speed. In Chapter 3, recovery of cautious gait behaviour over 12 weeks was examined. Less than half of the participants displayed recovered cautious gait behaviour and no predictors for recovery were identified. Overall, results from these shed light on the relationship between gait and cognition in the understudied population of community-dwelling adults. This thesis highlights clinically relevant findings. Clinical measures can be used to 1) distinguish between individuals, 2) predict results or outcomes, or 3) evaluate change over time (Kirshner & Guyatt, 1985). The results from this thesis show cautious gait behaviour, particularly in the Dual-task, can distinguish between individuals with and without concussion. Additionally, the evaluation of responsiveness and identification of MDC_{95} values of measures of cautious gait behaviour during the Dual-task condition identify performance during the Dual-task as a potential indicator of injury and recovery and provide an index of real change that can be used to monitor recovery.

4.1 Cautious gait behaviour: conscious or unconscious response?

While outside of the scope of the methods of this study, it is interesting to contemplate whether the cautious gait behaviour observed in individuals with concussion is a conscious or unconscious response to injury. In Chapter 2, results showed that the Concussion Group made fewer responses during the Dual-task than the Healthy Group. At a superficial level, interpretation of this finding may indicate that the Concussion Group placed more attention on their gait and therefore made less responses in the cognitive task. However, as previously discussed in Chapter 2, this finding suggests possible deficits in attention, executive function, and processing speed that imply the cautious gait behaviour observed was not consciously controlled. An interesting finding that may contradict this point is that cautious gait behaviour in the Self-paced task was higher in the Concussion Group than in the Healthy Group, despite the low cognitive load of this task which likely required no division of attention. It is possible then, that there are additional factors outside of cognitive dysfunction which may affect cautious gait behaviour.

Cautious gait behaviour is likely impacted by balance impairment after concussion. In a study that assessed balance in the same cohort of community-dwelling adults with concussion, balance deficits were found within 1 week after injury, though this was not affected by task difficulty likely due to insufficient difficulty of the balance task as discussed by the authors (Sweeny et al., 2021). Other studies have identified dynamic balance control deficits, characterized by decreases in peak anterior centre of mass (COM) velocity and increases in mediolateral COM velocity as task difficulty increases (Catena et al., 2007; Parker et al., 2005). It has previously been suggested that the decrease in AP COM velocity is reflective of the adoption of a cautious gait strategy, specifically in divided attention tasks. Parker et al. propose that the increased mediolateral sway is indicative of reduced ability to maintain stability in the frontal plane under divided attention conditions. It is possible that individuals with concussion perceive greater balance threats in the AP direction and therefore reduce their COM forward momentum. Given that during gait, the COM is within the base of support during the double support phases of the gait cycle, the results that indicate tighter control of anteroposterior COM sway are in line with the results of this thesis which found that double support time increased with task difficulty (Winter, 1995). Avoiding a fall while stepping during walking requires safe placement of the swing foot and therefore restabilization after taking a step takes place during the double support periods (Winter, 1995). Overall, it appears that individuals with concussion may experience a greater risk of falling in the anteroposterior direction and subsequently employ a more stabilizing or cautious response in instances of divided attention. However, whether this control of balance is consciously controlled requires more information using assessments such as the Movement-Specific Reinvestment Scale (Masters et al., 2005).

If individuals perceive threats to their stability during gait, assessing their balance confidence and fear of falling can provide insight with regards to whether the stabilization response is consciously employed or not. Poorer balance confidence is associated with an increase in double support time in individuals with stroke (Schinkel-Ivy et al., 2016, 2017), and Parkinson's Disease (Curtze et al., 2016). In older adults, fear of falling is associated with balance confidence (Moore & Ellis, 2008), as well as with higher cautious gait behaviour during single-task gait (Chamberlin et al., 2005) and dual-task gait (Donoghue et al., 2013). Although the relationships between balance confidence, fear of falling, and gait have not been investigated in the concussion literature, previous research has identified fear of falling and poor balance confidence in individuals with concussion (Alsalaheen et al., 2010; McGrath, 2008). It is possible then that cautious gait behaviour is a conscious strategy applied to increase stability in response to a fear of falling and poor balance confidence. This may especially be relevant in dual-task conditions. Previous research has identified that individuals will often devote their attention on processes associated with movement execution rather than the performance of a secondary task when experiencing fear of falling (Mak, Young, & Wong, 2020; Masters & Maxwell, 2008; Wulf et al., 2001). This allocation of cognitive resources to manage and monitor movement is known as reinvestment or conscious movement processing and may be a contributor to the cautious gait behaviour observed in individuals with concussion (Masters & Maxwell, 2008).

To truly understand whether cautious gait behaviour is a controlled response to instability or perceived instability, an individual's propensity to consciously process movement must be assessed. In older adults, a study found that greater conscious movement processing was associated with characteristics of cautious gait behaviour such as high double support time (Ellmers et al., 2021). Results from this thesis indicated that individuals with concussion displayed more cautious gait behaviour than the Healthy Group, therefore it is possible this cautious gait behaviour was consciously controlled. Conscious processing of movement, however, requires greater cognitive resources to plan and execute. Given that individuals with poorer cognitive function had greater cautious gait behaviour than the Healthy Group, reinvestment may not be the sole contributor to cautious gait behaviour. In addition, while it can be argued that the Concussion Group's cognitive scores were within normative values and therefore, they have the cognitive resources required to carry out consciously processed movements, it is important to note that 1) neuropsychological assessments are not always reflective of real cognitive deficits, and 2) performance on the Dual-task is impacted by cognition. Therefore, the cautious gait behaviour observed during a low cognitive task such as Self-paced walking may result in part due to conscious processing of movement, while in a more challenging task such as the Dual-task, there may be less propensity to consciously process movement and the cautious gait behaviour observed may be more in part due to cognitive deficits. How other factors such as balance confidence and fear of falling contribute to cautious gait behaviour and whether their association to cautious gait behaviour varies by task challenge is something future studies should investigate.

4.2 Revisiting the conceptual model

The conceptual model in Chapter 1 summarized the aim of this thesis, which was to characterize cautious gait behaviour and its moderators in community-dwelling individuals with concussion. In the original model, it was predicted that double support time and gait velocity would be features of cautious gait behaviour based on previous literature. However, based on the findings in Chapter 2, only double support time and cadence were statistically different between the Concussion and Healthy Group. In addition, symptom severity, cognitive function, and age were not able to predict recovery of cautious gait behaviour, though symptom severity and cognitive function were moderators of cautious gait behaviour within one week of injury in this population.

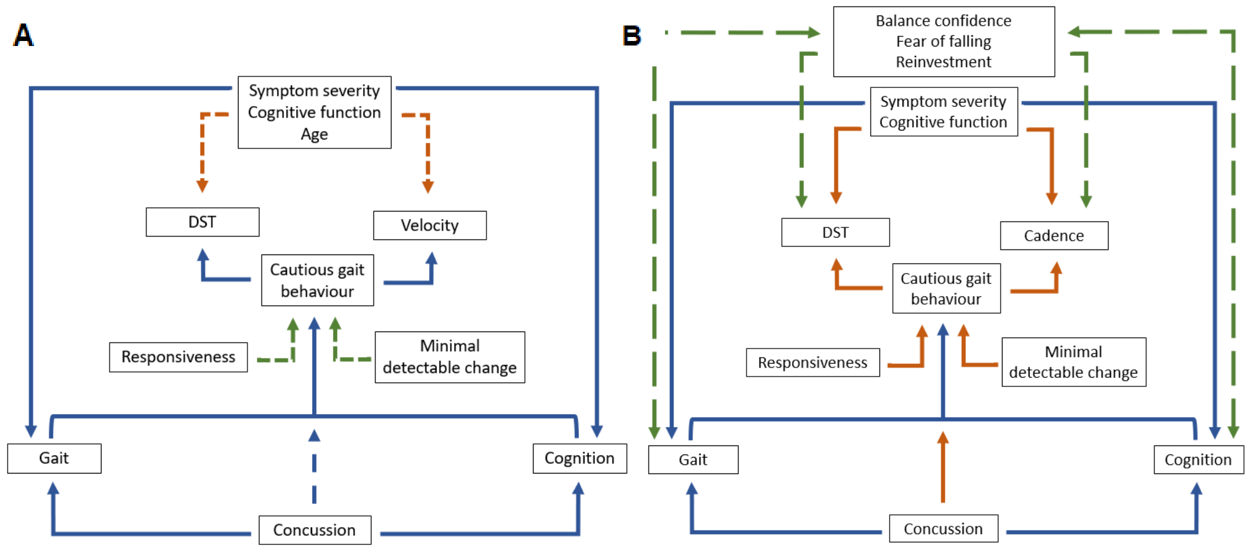

Figure 7. *A) Conceptual model introduced in Chapter 1. B) Revised conceptual model based on the findings of this thesis. Previously known relationships are presented in blue arrows. Orange arrows are relationships that were identified in this thesis. Green arrows represent relationships that were not investigated in this thesis but may be relevant contributors to the findings.*

The revised conceptual model identifies the impact of concussion on the relationship between gait and cognition and results in cautious gait behaviour. Acutely after injury, the level of cautious gait behaviour is affected by symptom severity and cognitive function. These findings have significant implications for the understanding of how concussion impacts community-dwelling individuals. Unlike previous studies which have identified gait velocity as a main component of cautious gait behaviour, this thesis indicates that gait velocity is not sensitive to gait and cognitive changes that can occur after concussion in community-dwelling adults. The findings also suggest that recovery may take up to three months or longer. However, in their Guideline for Concussion/Mild Traumatic Brain Injury, the Ontario Neurotrauma Foundation mentions that a full recovery of concussion symptoms, including cognitive functioning, occurs within a few days up to 1 to 3 months post-injury (Ontario

Neurotrauama Foundation, 2022). Our results indicate otherwise. While symptoms may resolve and cognitive assessments may suggest that cognitive functioning has recovered, subtle deficits may persist past three months. Management of concussion, specifically within community-dwelling adults, needs to consider these deficits that, while subtle, may still impact daily functioning.

Self-reported symptoms are widely used in concussion assessments. Objective measures of cognition such as the ImPACT are also commonly used. However, the results of this thesis suggest that these assessments may not be reflective of true impairment in patients. SCAT3, TMT-B, and PSI change scores were unable to predict recovery of cautious gait behaviour in this cohort. While the small sample size may have limited the power of these predictors, it is important to note that mean SCAT3 change score exceeded previously reported MDC_{95} values, and cognitive scores were normal at Week 1 and 12 (Lovell et al., 2006; Psychcorp, 2020; Tombaugh, 2004). Based on these assessments, participants would be considered cognitively healthy with likely resolved symptoms, however, as seen in Chapter 3, cautious gait behaviour was still present in a large proportion of the sample 12 weeks post-injury in the Dual-ask. Given the cognitive demands of the Dual-task, the presence of subtle cognitive deficits that cannot be detected by neuropsychological assessments cannot be overlooked. There is, however, the possibility that other factors were also responsible for the presence of cautious gait behaviour at Week 12. As previously discussed, balance confidence, fear of falling, and reinvestment may also contribute to cautious gait behaviour. The exact relationship between these factors and cautious gait behaviour in concussion are less established in the literature and require further investigation. Overall, these findings contribute in several ways to our understanding of how concussion impacts community-dwellings individuals and provide a basis for the inclusion of complex gait tasks such as the Dual-task in clinical settings.

4.3 Limitations and future studies

While this thesis sheds light onto the effects of concussion in community-dwelling adults, it is not without its limitations. Due to the retrospective nature of this study, choice of neuropsychological assessments to be analyzed was limited. It was not possible to assess attention using a test specific to the domain. Based on the Dual-task and the Coding and Symbol search subtests, it was possible to make inferences regarding potential deficits in divided attention. However, due to the multifaceted nature of cognition, it can be difficult to interpret results of assessments that test multiple cognitive domains or multiple sub-domains such as the Coding and Symbol search subtests (Calvillo & Irimia, 2020). Future studies should incorporate specific tests of attention to accurately evaluate this domain and its subdomains.

As previously mentioned, further work is needed to understand whether cautious gait behaviour in individuals with concussion is a controlled or unconscious response. To do so, fear of falling, balance confidence, and the propensity to consciously process movements should be assessed and their relation to cautious gait behaviour investigated. Doing so may inform treatment practices. For example, effects of inhibition training in older adults have been shown to be maintained for up to three years and may be relevant to inhibiting excessive conscious control of movement (Wilkinson & Yang, 2016).

This study suggests that cautious gait behaviour may be an indicator of injury and recovery in individuals with concussion. However, outside of research settings, assessment of cautious gait behaviour can be difficult as most clinical settings do not have access to gait measurement tools such as gait mats. To translate these findings for clinical use, alternative methods must be considered. Nowadays, most mobile devices and fitness watches are outfitted with motion sensors which can provide users with information on gait measures such as double support time. Future studies can assess the psychometric properties of such tools to accurately measure gait data in individuals with concussion. This will allow clinicians to assess their patients' gait characteristics without the use of expensive and often inaccessible tools such as gait mats.

4.4 Final conclusions

To conclude, this thesis characterized the relationship between gait and cognition in concussion by identifying the presence of cautious gait behaviour. This thesis also assessed the responsiveness of common gait measures and calculated MDC_{95} values to identify real change over time. Given the high responsiveness of all gait measures in the Dual-task and the Dual-task's ability to identify subtle impairments acutely after concussion, gait assessments that utilize the Dual-task should be incorporated into the assessment methods for concussion. By identifying the MDC_{95} for double support time and cadence, the main features of cautious gait behaviour, clinicians can determine when concussed patients' cautious gait behaviour has truly changed; this change can be further used to reflect recovery in gait and cognition. The findings of this thesis contribute to the sparse literature surrounding the effects of concussion in community-dwelling adults. In addition, the insights gained from this study may be of assistance to clinicians in evaluating and managing concussion in these patients to better inform treatment and return to life decisions.

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Appendices

Appendix A: Velocity matching

For each healthy individual, matches from the Concussion Group who matched on sex, age, and Dual-task velocity were found. Double support time versus velocity scatterplots for the healthy participants and concussion matches are presented in Figure A1. In the Self-paced condition, 73.9% of the concussion participants had a double support time greater than that of the healthy participants, 64.7% in the Talking condition, 50% in the Dual-task, and 57.1% in the Max-paced condition.

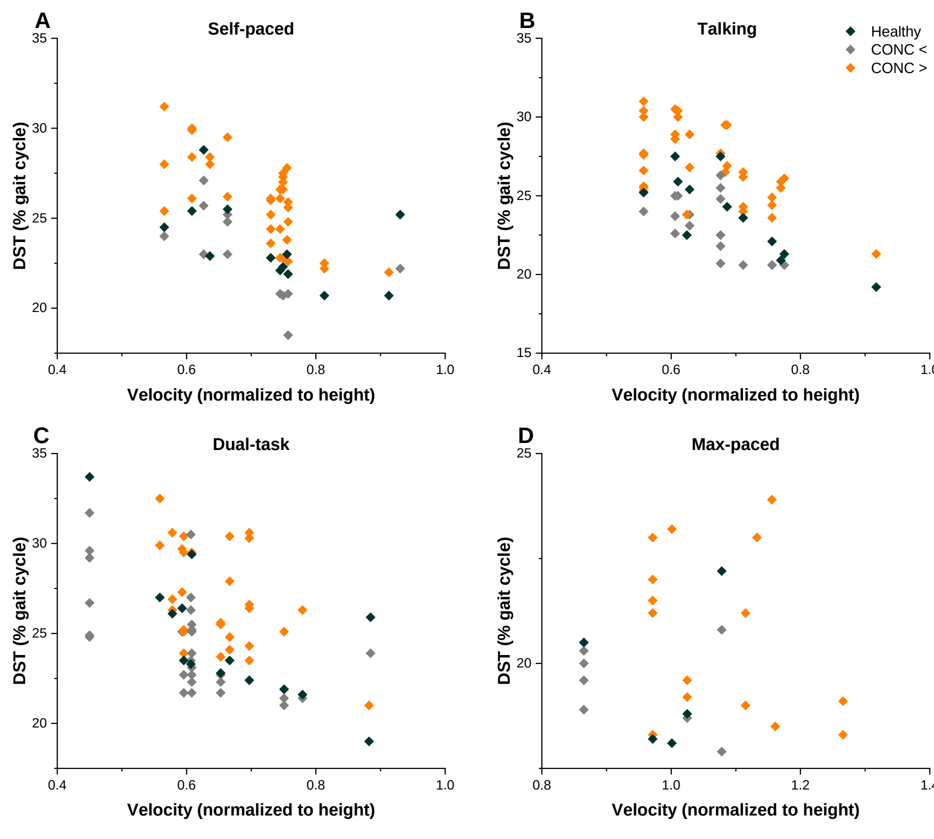

Figure A1. *Scatterplot of double support time of concussion and healthy participants matched on healthy velocity in each condition. A) Self-paced, B) Talking, C) Dual-task, D) Max-paced.*

Appendix B: Binomial logistic regression assumption tests for Chapter 3

Table B1. *Tolerance and variation of inflation values for all predictors.*

	Tolerance	Variance of inflation
SCAT3	.888	1.126
PSI	.973	1.028
TMT-B	.938	1.065
Age	.944	1.059

Table B2. *Significance values for predictor interaction terms for double support time regressions.*

	Self-paced	Talking	Dual-task
SCAT3 by lnSCAT3	.478	.321	.447
PSI by lnPSI	.378	.584	.255
TMT-B by lnTMT-B	.439	.044	.067
Age by lnAge	.868	.507	.506

Table B3. *Significance values for predictor interaction terms for velocity regressions.*

	Self-paced	**Talking**	**Dual-task**
SCAT3 by lnSCAT3	.560	.815	.665
PSI by lnPSI	.145	.378	.231
TMT-B by lnTMT-B	.371	.732	.816
Age by lnAge	.743	.901	.504

Table B4. *Significance values for predictor interaction terms for cadence regressions.*

	Self-paced	**Talking**	**Dual-task**
SCAT3 by lnSCAT3	.110	.317	.364
PSI by lnPSI	.092	.065	.192
TMT-B by lnTMT-B	.438	.569	.413
Age by lnAge	.482	.919	.723

Table B5. *Significance values for predictor interaction terms for step length regressions.*

	Self-paced	**Talking**	**Dual-task**
SCAT3 by lnSCAT3	.395	.202	.210
PSI by lnPSI	.244	.642	.128
TMT-B by lnTMT-B	.787	.352	.660
Age by lnAge	.303	.253	.479