EVALUATING PLANNED AND UNPLANNED GAIT TERMINATION DUAL-TASK COST IN INDIVIDUALS WITH AND WITHOUT A HISTORY OF CONCUSSION

by

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(Under the Direction of Robert Lynall

ABSTRACT

Complex and dual-task gait performance is altered following a concussion. Gait termination is one method of assessing complex gait performance. The purpose of our study was to determine how planned and unplanned gait termination with and without a cognitive load affected gait performance outcomes in individuals with and without a history of concussion. Physically active college-aged adults performed a series of planned and unplanned gait termination walking tasks on a Zeno Walkway, with and without serial subtraction (by 7s). We found that there were no differences in the dual-task cost of cognitive and gait performance outcomes between those with and without a history of concussion, suggesting that impairments in gait performance after concussion may resolve over time. Future research should assess the timeline of this potential recovery and evaluate complex and dual-task gait performance using novel methods. Word Count: 137

INDEX WORDS: Concussion, gait, walking, mild traumatic brain injury, dual-task cost

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LIST OF ABBREVIATIONS

COP	Center of Pressure
DTC	Dual-Task Cost
DT-Comp	Complex Dual-Task
DT-Simp	Simple Dual-Task
GTT	Gait Termination Time
LEMSK	Lower Extremity Musculoskeletal
SCAT	Sport Concussion Assessment Tool
SCOAT	Sport Concussion Office Assessment Tool
ST-Comp	Complex Single-Task
ST-Simp	Simple Single-Task

CHAPTER 1

INTRODUCTION

Gait is a fundamental part of human movement, with performance altered by several factors including musculoskeletal injury, aging, neurodegenerative diseases, substance use/abuse, and traumatic brain injury.[1] Concussion, a form of mild traumatic brain injury, is one prominent factor that can lead to changes in gait.[2] Individuals who are still in the acute stage after a concussion adopt a more conservative gait strategy characterized by decreased gait velocity and more time spent in the double-limb stance phase of gait.[2-5] These distinct changes have made gait analysis a well-established and useful tool for screening post-concussion and assessing recovery.[5,6]

Evaluating gait after injury is newly recommended by the 6th Concussion in Sport consensus statement, and single-task gait evaluations, defined as those without an added cognitive task, aid in assessing concussion recovery.[6] Performance on single-task gait generally aligns with symptom resolution, as expected, and may be associated with concussion severity.[2,7] In contrast, deficits in simple and complex gait performance during dual-task gait paradigms (DT-Simp and DT-Comp respectively) persist well into the asymptomatic time period.[5,8] Impairments in both levels of dual-task gait, and in some cases single-task complex (ST-Comp) gait (e.g., tandem gait), have been reported up to 2 months after concussion, and it is thought that these changes may remain even longer, particularly in DT-Comp gait tasks.[9] Dual-task cost (DTC) is a common measure of deficits in gait performance due to the addition of a cognitive task. It is defined as the percentage change between single-task and dual-task conditions and can help quantify the effect of dividing attention during a given task.[10]

Lingering impairments in gait performance are not the only contributors to a growing body of evidence pointing toward persistent neurophysiological impacts after traditional concussion recovery.[11] In addition to neurologically-based changes in locomotion, concussion is associated with an increased incidence of subsequent brain injury and lower extremity musculoskeletal (LEMSK) injury.[12,13] In high school, collegiate, and professional athletes, LEMSK injury risk is up to 2.5x greater in the year following a concussion when compared to the year prior to a concussion, and when compared to healthy controls.[14,15] Gait and dynamic postural control deficits present after a concussion have been hypothesized as factors contributing to this increased risk of musculoskeletal injury.[10,16] Impairments in feedforward and feedback mechanisms after concussion may contribute to alterations in gait and, downstream, may predispose one to sustaining a lower extremity injury.[17] Thus, neurophysiological changes, altered gait performance, and elevated LEMSK injury risk following a concussion appear to be tightly intertwined.[17]

Sport requires simultaneous areas of focus, much like dual-task gait requires the concurrent performance of a motor and cognitive task. Performing two or more tasks at the same time is commonly required in sport and many everyday activities, suggesting single-task locomotion does not adequately model the complex neurocognitive and motor demands of sport. For this reason, relying on single-task simple gait performance to inform sport readiness post-concussion is likely insufficient.[13] It is thought that adding a cognitive load requires the body to prioritize the mental task over the motor task, exhibiting previously masked deficits.[18,19] This phenomenon of dual-task prioritization may explain why dual-task and complex gait tasks have been the most sensitive to alterations in gait performance measures following a concussion.[18,19] Therefore, evaluating dual-task and complex gait may be more useful than simple single-task (ST-Simp) gait for clearing athletes to return to play post-concussion.

Several methods exist to assess complex gait performance.[5] One form of assessment, gait termination, is widely used in clinical practice, particularly in neurodegenerative conditions and the elderly population.[20,21] The use of gait termination time (GTT) in the sports rehabilitation setting is more novel and provides a functional measure of gait that, with the addition of a cognitive task, can be adapted from ST-Comp to DT-Comp to assess dual-task prioritization function during non-steady state walking, which more effectively replicates a sports environment.[22] Specifically assessing the dual-task cost of GTT can shed light on the prioritization that may occur when forcing attentional divide. This measure may be sensitive enough to pick up on subtle differences in gait, persisting into the asymptomatic period after a concussion, that may be significant in molding an appropriate return to play timeline and mitigating subsequent LEMSK injury risk.[5,22]

Gait termination can serve as an effective evaluation method of complex gait and has been used to assess gait acutely and subacutely after a concussion.[23] However, it remains unknown if a history of concussion can alter performance on this task. There may still be gait and motor control deficits present months and even years after initial injury, and evaluation of this potential deficit would prove to be valuable. If having merely a history of concussion is associated with impaired gait termination, then the period of increased risk of LEMSK injury after concussion may be longer than is currently expected. Therefore, the purpose of this study was to determine how planned and unplanned gait termination with and without an added cognitive load affected dual-task cost outcomes, including cognitive task response rate and accuracy, gait termination time and clinical spatiotemporal gait measures in adults with and without a history of concussion.

We hypothesized that the dual-task costs of cognitive and spatiotemporal gait measures would be higher in those with a history of concussion and that these differences would become more pronounced as the complexity of the motor task increased (i.e., going from planned to unplanned gait termination). Essentially, we expected that dual-task cost gait (regardless of whether it is planned or unplanned) would differ between groups, but that this difference would be greater during the unplanned gait termination condition, since the complexity of the motor task is greater. This is hypothesized to present as comparatively higher dual-task costs in the concussion history group when comparing unplanned and planned gait termination, relative to those without a concussion history.

CHAPTER 2

LITERATURE REVIEW

Concussion

Epidemiology

Concussion, a form of mild traumatic brain injury (mTBI), is a common athletic injury with a substantial public health and economic burden.[24,25] Concussion is considered a major health disorder by the Centers for Disease Control and Prevention (CDC), and it is currently estimated that up to 3.8 million sports related concussions occur each year in the United States, with treatment costs exceeding $60 million per year.[24,25] Moreover, it is expected that the rate of concussions in a given year is greatly underestimated, as many individuals that sustain a concussion do not seek medical advice.[26]

Concussion is defined as a "traumatic brain injury caused by a direct blow to the head, neck or body resulting in an impulsive force being transmitted to the brain."[6] It is typically presented as a clinical diagnosis and characterized by several multi-system symptoms, potentially including headache, fatigue, neck pain, mood changes, dizziness, sensitivity to light and noise (photophobia and phonophobia), and cognitive changes.[6]

Neurometabolic Basis of Concussion

The underlying neurological changes that begin at the moment of injury are notably outlined in Giza and Hovda's review of the neurometabolic cascade.[27] Neurons undergo structural and functional changes that elicit a variety of downstream effects. This cascade has been defined as a 7-step process, including ionic flux and glutamate release, energy crisis, cytoskeleton damage, axonal dysfunction, altered neurotransmission, inflammation, and potential cell death.[27] The wide range of symptoms observed in concussion can be attributed to the diffuse nature of the elements comprising the neurometabolic cascade, and the timing of the cascade can vary greatly from person to person. However, in general, the cascade is thought to coincide with the common multi-system concussion symptoms and to proceed along the clinical timeline for recovery, which is projected to fall around 14 days post injury.[6] While several studies report symptom resolution closer to 5-10 days post injury, other studies evidence physiological deficits for at least 15-30 days post-concussion, persisting even after clinical deficits resolve.[26] In that vein, second messenger systems generated by the neurometabolic cascade can continue to alter neurons well after a concussion, and, in theory, contribute to subacute symptoms and potential long-term effects of concussion.[27]

Clinical Tools for Diagnosing Concussion

There are several clinical tools used to diagnose concussion. Commonly used diagnostic tools include symptom scales, balance assessments (BESS), neurocognitive examinations (ImPACT, CNS Vital Signs, etc.), vestibular/ocular motor assessments (VOMS), and multi-modal concussion assessment tools (SCAT-6/SCOAT-6, Sway, etc.).[6,28-30]

The most recent version of the Sport Concussion Assessment Tool (SCAT-6) is a common evaluation tool for sideline use, with the greatest reliability when administered in the first 72 hours after injury.[6] Alternatively, the Sport Concussion Office Assessment Tool (SCOAT-6) was developed specifically for serial testing to occur outside of the acute, sideline environment and ultimately track improvements.[6] Importantly, both tools include an optional subsection of timed tandem gait and dual-task gait, which aligns with recommendations to assess dynamic balance and dual-task performance after concussion.[6] Complex and dual-task gait measures are able to detect abnormalities up to two months after injury, well after symptom resolution and return to sport.[9] Thus, concussion assessment tools, such as the dual task gait subsection of the SCAT-6/SCOAT-6 may be more helpful in ultimately determining readiness to begin the graduated return to activity, learning, and driving after a concussion, compared to earlier subsections in the assessment tool.[6]

Increased Risk of Lower Extremity Musculoskeletal Injury After Concussion

Concussion has been widely accepted as a factor that is associated with the increased risk of lower extremity musculoskeletal injury.[12-17] A study of 102 college-aged athletes found that in the year following a concussion, LEMSK injury risk is up to 2x elevated compared to year prior to sustaining a concussion.[14] In another study, LEMSK injury risk in a group of collegiate athletes was up to 2.5x more elevated compared to healthy controls in the 90 days following a concussion.[15] The increased risk of LEMSK injury after concussion could be linked to deficits observed in gait performance after concussion.[17]

Relationship Between Gait and LEMSK Risk After Concussion

A study of 34 collegiate athletes found that individuals who sustained a LEMSK injury after concussion exhibited decreased cognitive accuracy during dual-task gait as well as decreased gait speed and greater time in double limb support during both single and dual-task gait. Moreover, these conservative gait strategies were found to be present both before and after concussion in those with a subsequent LEMSK injury, suggesting that evaluating gait performance even before a concussion may aid in assessing future injury risk.[16] It is hypothesized that gait performance falls under a larger umbrella of altered motor function after a concussion and contributes to the observed increase in LEMSK injury risk after concussion.[12,17] Thus, evaluating gait performance after a concussion may be helpful in determining subsequent LEMSK injury risk.[16]

Gait

Gait is the study of human locomotion, which serves as a fundamental part of movement.[1] Gait exists as a cycle with two main phases: the stance phase and the swing phase. These phases describe the action of a single limb during the gait cycle and are central to clinical gait evaluation.[31] Identifying the stage of gait in which impairments are exhibited is critical information for evaluating function or determining underlying pathology.[31,32] For example, more time spent in the single limb stages of the swing phase on a particular limb, compensating for the opposite limb, may indicate an antalgic gait, often associated with lower extremity injury.[31,32] Clinical spatiotemporal gait outcomes are also important for the evaluation of gait, and work in conjunction with the phases and stages of gait when analyzing locomotion. A wider base of support, shorter step length, or greater time spent in double stance, for example, may indicate balance deficits.[31-33] Evaluating spatiotemporal gait characteristics also allows for the quantification of differences in gait, which is important when comparing to a baseline or normative data.[32]

For the purpose of evaluation, gait can be broken down into different conditions based on the task's level of complexity. Simple gait is defined as walking in a straight line on a flat surface, while complex gait includes the addition of challenges to the motor system, such as surface or directional changes, altered foot placement (i.e., tandem gait), or interruptions to non-steady state walking. Common methods for evaluating complex gait performance include obstacle step-over tasks, turning, and gait initiation and termination, the latter of which being the focus in this study.[5]

In addition to being characterized as either simple or complex, gait can also be divided based upon the presence of a cognitive task. Dual-task gait, in contrast to single-task gait, includes a simultaneous cognitive task, such as auditory or visual Stroop tests or question and answer tasks.[5] These can be combined to specifically evaluate ST-Simp, ST-Comp, DT-Simp, and DT-Comp gait, and compare outcomes from each.

Deficits in Gait Performance After Concussion

ST-Simp gait, the most basic form of gait performance, was found on average to return to normal 5 days after a concussion, with less than a quarter of studies in a 2018 review detecting abnormalities outside the acute period.[5] Alternatively, impairments during simple and complex dual-task gait were detected into the subacute phase in 95% of the included studies.[5] In addition, individuals have been found to exhibit slower walking velocity and greater frontal plane sway during dual-task gait, but not single-task gait, up to two months after a concussion compared to controls.[9] There seems to be consensus that ST-Simp gait is impaired during the acute phase of concussion, returning to normal in about 5 days, while dual-task and complex gait is impaired into the subacute phase of injury, often well past return-to-play periods. It is not well understood whether these impairments similarly persist into the chronic time point. However, there is strong evidence supporting the use of dual-task gait, particularly DT-Comp, to evaluate gait performance when looking outside the acute phase of concussion.[5,9]

While DT-Comp gait is helpful in assessing gait in the subacute and chronic phases of concussion recovery, less is known about the effect of general concussion history on gait performance.[3,9] There are a handful of studies that have reported alterations in gait performance in those with a history of concussion.[3,34,35] One study, consisting of 68 college-aged individuals found that those with a history of concussion spent more time in double leg stance and had slower gait velocity during single task and dual task gait, compared to healthy controls.[34] However, in a more recent study of adults across different age groups (20-60+), a history of <3 concussions sustained in high school did not affect gait performance during any of the ST-Simp, ST-Comp, DT-Simp, and DT-Comp tasks.[36]

Dual-Task Cost

Dual-task cost (DTC) expresses the amount of change that occurs when a task requires attention to be divided.[10] It is defined as the difference between dual-task and single-task performance, divided by single-task performance, expressed as a percentage.[37] A higher percentage indicates a worse dual-task performance and therefore would indicate a greater difference between single and dual-task results.[37] Dual-task cost gait measurements have been used in concussion research to differentiate between concussion and non-concussion groups,[37] sports-related and non-sports-related concussion groups,[38] between males and females with concussion,[39] and to compare results after concussion to subsequent sport-related injury incidence.[10] The latter study assessed dual-task gait cost in 42 adolescent athletes, both acutely after concussion and after clinical recovery, and collected subsequent injury information in the year following concussion. It was found that athletes with dual-task gait costs that worsened during the course of concussion recovery were associated with subsequent sport-related injury in the year following concussion.[10] This further supports the concept that deficits in gait performance after concussion may predispose one to sustaining a LEMSK injury after concussion. It also supports the use of DTC outcomes in gait and concussion-related research.[10]

Gait Termination

Previously, gait termination has been used in a variety of populations: elderly, healthy and physically active, and those with a neurodegenerative disorder, as both single and dual task measures.[20-22] Johnson et al. paired planned and unplanned gait termination with a visual Stroop task in healthy individuals to create a dual-task complex gait paradigm, and compared findings with the same tasks performed without the added Stroop test (comparing ST-Comp and DT-Comp). It was found that gait velocity was slower during the dual-task trials compared to the single-task trials and reaction time worsened with the increasing complexity of the task.[22]

In addition, gait termination has been used to evaluate single task complex gait in the acute and subacute time periods after concussion in a group of 47 college-aged individuals.[23] It was found that gait velocity was only different acutely after a concussion, while alterations in braking and propulsion were present acutely and additionally persisted into the subacute phase. Importantly, scores on clinical concussion tests had returned to baseline in all participants in the concussion group by the day 10 post-injury time point, indicating that gait termination was sensitive enough to pick up on subtle, but significant, changes in gait performance after the assumed point of full recovery.[23]

While gait termination has been shown to be useful in evaluating ST-Simp and ST-Comp gait after a concussion, to date, no study has used gait termination in a dual-task paradigm (using ST-Comp and DT-Comp) post-concussion or used gait termination to determine the effect of concussion history on the dual-task cost of gait performance and cognitive outcomes.

CHAPTER 3

METHODS

Participants

College aged individuals, who self-reported being physically active for at least 90 minutes per week, were included in this study and placed into either the concussion history group or no concussion history group.[40] Concussion history was self-reported and collected using the Michigan TBI Identification Method form.[41] In accordance with the 6th international concussion in sport consensus statement, concussion was defined as a "traumatic brain injury caused by a direct blow to the head, neck or body resulting in an impulsive force being transmitted to the brain."[6] Participants were categorized into the concussion history group if they reported 1 or more concussions or were determined as having no concussion history if they reported 0 prior concussions on the reporting form.

Participants with concussion history were excluded if they self-reported that they were admitted to the hospital following their concussion or had positive imaging findings due to their concussion.[42] We did not exclude participants based on number of prior concussions and time since most recent concussion, but this information was recorded. All participants were excluded if they self-reported having attention deficit hyperactivity disorder, uncorrected vision problems, history of neurological disease, history of seizures, structural brain lesions (e.g., stroke), were currently using antidepressants, were currently experiencing a high fever, or were undergoing immunosuppressive therapy.

Control group participants were matched to concussed group participants by age (±2 years), sex, and body mass index (±2 kg/m^2). Participants were recruited from across the university through various methods including listserv postings, flyers, and in-class verbal recruitment.[43,44] The study was approved by the Institutional Review Board and all participants reviewed and signed consent documentation prior to data collection.

Demographics

Demographic information included age, sex, height, mass, Sport Concussion Assessment Tool symptom inventory, Godin Leisure Activity Questionnaire, and dominant limb. Dominant was defined as which limb participants prefer to kick a soccer ball for distance.[45] Participants were given the Michigan TBI Identification Method form (Supplementary Figure 3).[41] If participants did not remember the exact details for their concussion date, a month and year sufficed. If participants did not remember other details, they were instructed to leave the section blank or write "unknown."

Godin Leisure Activity Questionnaire

The Godin Leisure Activity Questionnaire[46] was collected to better quantify physical activity between groups. The Godin Leisure Activity Questionnaire is a self-reported measure of physical activity at 3 levels: strenuous exercise, moderate exercise, and mid/light exercise.[46] Participants responded by writing down a value that indicates the number of times they participate in each of the 3 levels of physical activity per week (7 days) for at least 15 minutes.[47] The participant's written number was multiplied by a constant provided by the questionnaire for each level of physical activity and then summed together for analysis. Higher scores indicate higher levels of physical activity.

Sport Concussion Assessment Tool Symptom Inventory

The Sport Concussion Assessment Tool – 5th Edition was used to ensure that participants were not experiencing clinically significant concussion symptoms at the time of data collection.[48] The Sport Concussion Assessment Tool symptom inventory is a 22 symptom (e.g., headache, nausea, trouble falling asleep) checklist, with each symptom scored on a Likert scale from 0 to 6, with 0 indicating the symptom is not present and 6 indicating the symptom is present and severe.[48] The total number of symptoms was calculated by adding the number of symptoms present (i.e., anything reported above a 0) with a range of 0 to 22.[49] Symptom severity was calculated by summing the individual severity values from each symptom making the total score range from 0 to 132.[49] Higher scores for both outcomes indicate a more severe symptom presentation.

Single- and Dual-Task Baseline

Prior to single- and dual- task gait trials, baseline serial subtraction was completed. Participants were seated in a chair and instructed to perform serial subtraction by 7s from a random number between 90 and 200, as quickly and as accurately as possible.[50] Baseline serial subtraction trials lasted 20 seconds each. One practice trial (not recorded) and 3 audio-recorded trials were completed. Scoring occurred at a later date (Table 1).

Table 1. Cognitive outcome descriptions

Outcome	Description
Dual-Task Cost Response Rate	Response rate dual-task performance relative to single-task (percent; Equation 1). Response rate was defined as: the total number of responses spoken during a given amount of time. Time was 20 seconds for baseline serial subtraction and varied for gait trials (total responses/second).
Dual-Task Cost Accuracy	Response accuracy dual-task performance relative to single-task (percent; Equation 1). Response accuracy was defined as: the percentage of correct responses spoken throughout the trial ([correct responses/attempts]×100; % correct).

Single- and Dual-Task Planned and Unplanned Gait

All gait tasks were collected on a 6.1x0.61m Zeno Walkway (Protokinetics, Havertown, PA). The walkway reported step length and width in centimeters (cm) and velocity in centimeters per second (cm/s), however we converted these measures to meters (m) and meters per second (m/s), respectively, prior to calculating DTC (Table 2; Equation 1). For both planned and unplanned gait termination tasks, participants began on the walkway and were told to “get set.” The “get set” instruction was to cue participants to keep still until they heard the audible buzzer sound and could initiate walking. Participants were instructed to begin walking at a self-determined pace immediately after hearing the sound, which occurred 2-5 seconds after the “get set” cue, as selected by the test administrator.[40]

For planned gait termination, participants were instructed to stop at a piece of tape at the end of the walkway. For unplanned gait, the same buzzer that initiated gait was manually triggered at a random point during the walking task to cue gait termination.[43] Gait termination time was calculated using center of pressure data from the gait mat and was recorded in seconds (Table 2).[22] During the unplanned gait termination, “catch” trials were also included. A catch trial is where the buzzer cueing gait termination did not sound, but the participant expected it would, due to the nature of the trial condition. The purpose of catch trials was to keep the participant from anticipating gait termination. The participant was made aware that catch trials may be included, but unaware when they would occur. The unplanned gait termination for each participant included at least one catch trial.

Table 2. Gait outcome variable descriptions

Outcomes	Description
Spatiotemporal	
Dual-Task Cost Velocity	Velocity of dual-task gait relative to single task (percent; Equation 1). Velocity was defined as: the sum of all stride lengths divided by the sum of all stride times (m/s).
Dual-Task Cost Step Length	Step length during dual-task gait relative to single task (percent; Equation 1). Step length was defined as: the anteroposterior distance between both feet during double limb support (m).
Dual-Task Cost Step Width	Step width during dual-task gait relative to single task (percent; Equation 1). Step width was defined as: the mediolateral distance between both feet during double limb support (m).
Dual-Task Cost Gait Termination Time	Gait termination time dual-task performance relative to single task (percent; Equation 1). Gait termination time was defined as: the time from the third to last step until the center of pressure (COP) velocity matched the COP velocity prior to initiating gait.[22]

Equation 1: $$\left(\frac{(dual-task\ performance)-(single-task\ performance)}{(single-task\ performance)}\right)\times 100$$

For dual-task conditions, participants were provided the following instructions: “Please count backward by 7s, get set, 100.” In this example, 100 represents the number the participant repeated back and began serial subtraction from. The starting number of 100 changed randomly between 90-200 for each condition performed. Participants began counting after the instructions were given, and, like the single-task gait trials, the audible cue randomly sounded 2-5 seconds after participants got “set” and began counting. Audio was recorded during gait to score the serial subtraction (Table 1).

One practice trial for each motor and cognitive condition was given. Three total trials for each condition (12 total trials) were collected for analysis. All practice trials and any catch trials performed during single- or dual-task unplanned gait were not included.

Procedures

Informed consent and demographic information, as described earlier, were collected from each participant upon arrival. If the participant met the inclusion and exclusion criteria, they continued with the data collection session. The participant first completed baseline serial subtraction by 7s, and then began the single and dual-task planned and unplanned gait trials. Each condition was completed in its entirety before switching (e.g., participants finished all three trials of the single task unplanned gait termination before moving to the next condition). The order of the four gait conditions was randomized for each participant, but single task always came before dual-task. Baseline and cognitive task scoring, and cognitive and gait outcome analysis occurred at a later time.

Data Analysis

A 2 (planned and unplanned) x 2 (control vs concussion history) analysis of variance was used. Tukey post hoc tests were applied to any significant interactions. Dependent variables were the dual-task cost for the following gait outcomes: step length, step width, step velocity, and gait termination time (Table 2). Cognitive dependent variables were dual-task cost response rate and dual-task cost response accuracy (Table 1). Dual-task costs were calculated using Equation 1. For the purposes of our discussion, a positive value represents worse performance during the dual-task relative to the single-task.

CHAPTER 4

RESULTS

Demographics

A total of 34 college-aged, physically active individuals participated in this study. Of these individuals, 20 reported sustaining a concussion in their lifetime. One subject in the concussion history group was excluded from gait outcome analysis due to incomplete data. The sample eligible for complete analysis was 19 participants with a history of concussion (58%) and 14 participants with no history of concussion (42%). There were no significant differences in demographic variables. Participant demographic information is outlined in Table 3.

Table 3. Demographic characteristics comparisons between the concussion history group and no concussion history group. Mean (95% confidence interval) are presented.

	Concussion (n=20)	**Control (n=14)**	**p-value**	**Effect size[a]**
Age (years)	20.1 [19.2, 20.9]	20.6 [19.4, 21.9]	0.387	0.299
Height (m)	1.74 [1.69, 1.78]	1.70 [1.65, 1.75]	0.231	0.415
Gender (% female)	n=12 (60.0%)	n=7 (50.0%)	0.728	1.500
Mass (kg)	69.3 [64.6, 74.1]	64.1 [59.3, 69.0]	0.127	0.534
BMI	22.9 [21.8, 24.0]	22.2 [21.0, 23.4]	0.378	0.304
Months Since Most Recent Concussion	35.3 [29.6, 41.0] Range 1-96	--	--	--
Concussion Frequency	1 n=7 (35.0%) 2 n=5 (25.0%) 3+ n=8 (40.0%)	--	--	--
Godin Leisure time Physical Activity	64.5 [52.3, 76.7]	64.6 [46.2, 83.0]	0.994	0.002
Lower Extremity Functional Scale	79.0 [78.4, 79.6]	78.4 [77.0, 79.9]	0.381	0.302
Dominant Leg (% Right)	n=19 (95.0%)	n=10 (71.4%)	0.134	0.132
SCAT Total Symptoms	1.7 [0.8, 2.6]	0.6 [0.0, 1.3]	0.079	0.617
SCAT Symptom Severity	2.0 [0.8, 3.2]	0.8 [0.0, 1.5]	0.106	0.566

a. All effect sizes were calculated using Hedge's g, except for gender and dominant leg for which p-values were calculated with Fisher's exact tests and effect sizes were calculated using odds ratios.

Cognitive Outcomes

There was no significant interaction between gait termination and group for the dual-task cost of response rate or response accuracy (Table 4). In the concussion history group, there was a mean 3.51% and 0.73% dual-task cost for response accuracy for planned and unplanned gait, respectively. In comparison, there was an average 3.23% and 5.13% dual-task improvement (opposite of cost) in the control group for planned and unplanned gait. For total response rate, there was an average 15.28% and 13.95% DTC in the concussion group and an average 19.87% and 7.63% DTC in the control group for planned and unplanned gait, respectively (Table 4). Effect sizes were small for all interactions, apart from DTC response accuracy for planned gait, which was moderate.

Table 4. Dual-task cost cognitive outcomes comparisons between the concussion history and no concussion history group. Mean (95% CI) are presented.

	Concussion (n=18)	**Control (n=9)**	**p-value**	**Effect size[a]**
Planned Gait - Dual-Task Cost				
Percent Correct	3.51 [-1.80, 8.82]	-3.23 [-13.11, 6.65]	0.161	0.572
Total Response Rate	15.28 [4.41, 26.15]	19.87 [3.87, 35.86]	0.607	0.206
Unplanned Gait - Dual-Task Cost				
Percent Correct	0.73 [-11.98, 13.43]	-5.13 [-11.31, 1.05]	0.512	0.264
Total Response Rate	13.95 [1.84, 26.07]	7.63 [-3.78, 19.04]	0.483	0.282

a. All effect sizes were calculated using Hedge's g.
A positive value represents worse performance during the dual-task relative to the single-task.

Gait Outcomes

There was no significant interaction between gait termination and group for the dual-task cost of step length (p = 0.70, η_p^2 = <0.01), step width (p = 0.69, η_p^2 = <0.01, velocity (p = 0.28, η_p^2 = 0.04), or gait termination time (p = 0.86 η_p^2 = <0.01). In the concussion history group, mean DTC for gait termination time was 16.92% for planned gait and 17.76% for unplanned gait. In the control group, average DTC for GTT was 44.21% and 50.34% for planned and unplanned gait, respectively. Effect sizes were small for all variables, and we did not observe any main effects for group or gait conditions (Table 6).

Table 5. Dual-task cost gait outcomes comparisons between the concussion history and no concussion history group. Mean (±SD) are presented.

	Concussion (n=19)	**Control (n=14)**
Planned Gait – Dual-Task Cost		
Step Length	9.00 (6.30)	10.02 (8.42)
Step Width	12.91 (24.30)	14.73 (20.72)
Velocity	14.65 (9.32)	16.61 (12.20)
Gait Termination Time	16.92 (51.98)	44.21 (87.63)
Unplanned Gait – Dual-Task Cost		
Step Length	9.40 (5.08)	11.7 (7.77)
Step Width	13.05 (22.92)	11.11 (20.39)
Velocity	14.79 (8.32)	19.87 (14.94)
Gait Termination Time	17.76 (49.23)	50.34 (90.23)

A positive value represents worse performance during the dual-task relative to the single-task.

Table 6. 2x2 ANOVA results with group and gait condition main effects.

	Step Length		**Step Width**		**Velocity**		**Gait Termination Time**	
	p-value	Effect size[a]	p-value	Effect size[a]	p-value	Effect size[a]	p-value	Effect size[a]
Interaction	0.70	<0.01	0.69	<0.01	0.28	0.04	0.86	<0.01
Group	0.54	0.01	0.99	<0.01	0.34	0.03	0.13	0.07
Gait	0.41	0.02	0.69	<0.01	0.24	0.04	0.81	<0.01

a. All effect sizes were calculated using partial eta squared.

CHAPTER 5

DISCUSSION

In this study, we found no evident differences in the dual-task costs of cognitive and spatiotemporal gait measures between those with and without a history of concussion. In addition, our data did not support the hypothesis that gait performance on a more complex task (i.e., unplanned vs. planned gait termination) would be affected by group. Our findings are in agreement with those of Martini et al., who found history of concussion to have no effect on single or dual-task gait performance.[36]

While our findings do not indicate differences in dual-task gait cost between those with and without a history of concussion, our results contrast evidence that demonstrate poorer complex and dual-task gait acutely and subacutely after concussion.[5,8] Impairments in both simple dual-task (DT-Simp) and complex dual-task (DT-Comp) gait, and complex single-task (ST-Comp) gait (e.g., tandem gait), have been consistently reported up to 2 months after concussion, even after symptom resolution.[9] Our study used single- and dual-task planned and unplanned gait termination (a ST-Comp/DT-Comp gait paradigm) in those with and without a history of concussion, making time point the obvious differing factor between our investigation and ones included in prior systematic reviews and meta analyses.[5,9] In our study, in the group with a history of concussion, the average time span from most recent concussion timepoint was 35.3 months, or nearly 3 years (Table 3). This is significantly greater than 2 months from injury, as studied previously.[9] Thus, our results suggest that complex and dual-task gait performance differences resolve at some point between 2 months and up to several years after concussion.

It is thought that impairments in gait and postural control contribute to the established increased risk of LEMSK injury.[16,17] Previous literature suggests that LEMSK injury risk is up to 2.5x higher in the year following a concussion compared to the year prior to a concussion and compared to healthy controls.[14,15] While impairments in gait may persist well after symptom resolution and return to sport, and are thought to contribute to an increased risk of LEMSK injury, these deficits may resolve at some point during or after the first year following a concussion.[10,16] In addition to gait and postural control impairments as an explanation for increased LEMSK injury risk after concussion, altered lower extremity somatosensation due to central processing impairments has been proposed as a contributing factor.[17,51] In a study by Chong et al., they included use of functional magnetic resonance imaging (fMRI) in individuals after a concussion. Their results reported improvement of somatosensory cortical connectivity after five months, but not after one month.[52] If somatosensory impairments are indeed a contributing factor in LEMSK injury risk, and possibly intertwined with the central processing and neural integration of gait and postural control, then investigating complex and dual-task gait before and after the five month recovery timeline previously found may be helpful in determining a timeline of gait performance recovery. There were participants in our study who sustained a concussion less than 5 months before data collection, as time since most recent concussion ranged from 1 to 96 months (Table 3). Performing a time since concussion correlation of DTC outcomes in the concussion history group may be valuable in determining a timeline of gait performance recovery after concussion. That said, not all concussion history group participants in our study may have experienced symptoms of motor impairment or had injury to areas of the brain modulating gait with their concussion(s). Thus, a heterogenous concussion sample in this study may have contributed in part to our null findings.

To our knowledge, this study was the first to use gait termination to assess gait performance in those with a history of concussion. Gait termination challenges centrally mediated motor control mechanisms and is an effective evaluation method of complex gait, as demonstrated in healthy individuals and those in the acute and subacute period after a concussion.[22,23] Alterations in gait velocity, propulsion, and braking during planned gait termination both one day and ten days after concussion have been reported.[23] Our study was the first to use planned and unplanned gait termination to evaluate complex gait in individuals greater than 10 days post-concussion and to assess dual-task cost. Gait termination is one way to investigate non-steady state walking and can serve the purpose of better modeling the complex motor demands of gait in sport compared to simple, straight path walking.[13,19] A prior study performed by Johnson et al. in our lab found differences between planned and unplanned gait performance regardless of concussion history, however our results did not coincide with theirs as we did not observe a main effect for planned vs. unplanned gait.[22] It should be noted, however, that Johnson and colleagues assessed raw single- and dual-task values, while we assessed the dual task cost (DTC) of planned vs. unplanned gait termination. Our findings in this context may suggest that participants had a similar magnitude of impairment in both single and dual-task conditions, and the extent of this impairment (i.e., DTC) did not change between planned and unplanned gait even if unplanned gait performance was worse, for example. Even so, despite planned/unplanned gait termination in previous studies being sufficient to expose alterations in ST-Comp and DT-Comp gait performance, there may exist a paradigm of complex gait with a greater motor demand, such as figure-of-8 walking or obstacle crossing, or even a non-gait motor task, that elicits a more significant dual-task cost in those with a history of concussion.[5,22,23] It is approximated that impairments in turning gait persist up to one year after concussion.[53] Therefore, investigating dual-task cost of turning gait, or developing complex gait paradigms combining turning, obstacle crossing, and planned/unplanned gait termination may offer insights into the extent and persistence of gait impairments in those with a concussion history.[5,34,53]

This study is not without limitations. Participants self-reported their concussion history and the reported time since injury varied from 1 to 96 months (Table 3). Time since most recent concussion was large and variable, which may have affected our outcomes if there exists a point when impairments in complex and dual-task gait performance resolve. Future research should evaluate gait performance at different periods following a concussion, or perform a longitudinal analysis, to determine a timeline of this potential resolution. Due to the limited size of the gait walkway, only 3-6 footfalls were captured per trial and subsequently included in spatiotemporal outcome analysis. This may have led to the loss of certain data and eventually to the removal of one subject from data analysis due to data loss. Additionally, since there was only a small amount of space on the mat to press the buzzer after walking had begun, participants may have slowed down as they reached the edge of the mat. This could affect our outcomes; however multiple trials were assessed and catch trials were included to minimize anticipation of the buzzer cueing gait termination. Variability in gait termination trials may be reflected in the large standard deviations seen for mean DTC GTT (Table 5). This could be due to varying participant reactions to the buzzer during unplanned gait termination and a wide range of gait termination strategies. Future studies evaluating GTT should ensure that the buzzer is pressed at the same time during the gait cycle (i.e., upon heel strike) during unplanned gait termination and re-collect trials where participants do not stop in a natural progression. Lastly, while gait termination time has been shown to be an effective measure of complex gait, it may not be capable of modeling the full motor complexity of a sports environment. Another complex gait paradigm such as tandem gait, figure-of-8 walking, or obstacle crossing may be more sensitive in picking up deficits due to dual-task prioritization.

CHAPTER 6

CONCLUSION

This study aimed to determine how planned and unplanned gait termination with and without an added cognitive load affected cognitive and gait performance outcomes, including gait termination time and clinical spatiotemporal gait measures in adults with and without a history of concussion. We found that there were no differences in the dual-task cost of cognitive and gait performance outcomes between individuals with and without a history of concussion. This suggests that deficits in gait performance may resolve at some point after concussion, and this recovery of function may occur outside of the period of elevated LEMSK injury risk following a concussion. Future research should evaluate this concept in those with a history of concussion and establish a timeline for proposed gait performance recovery.

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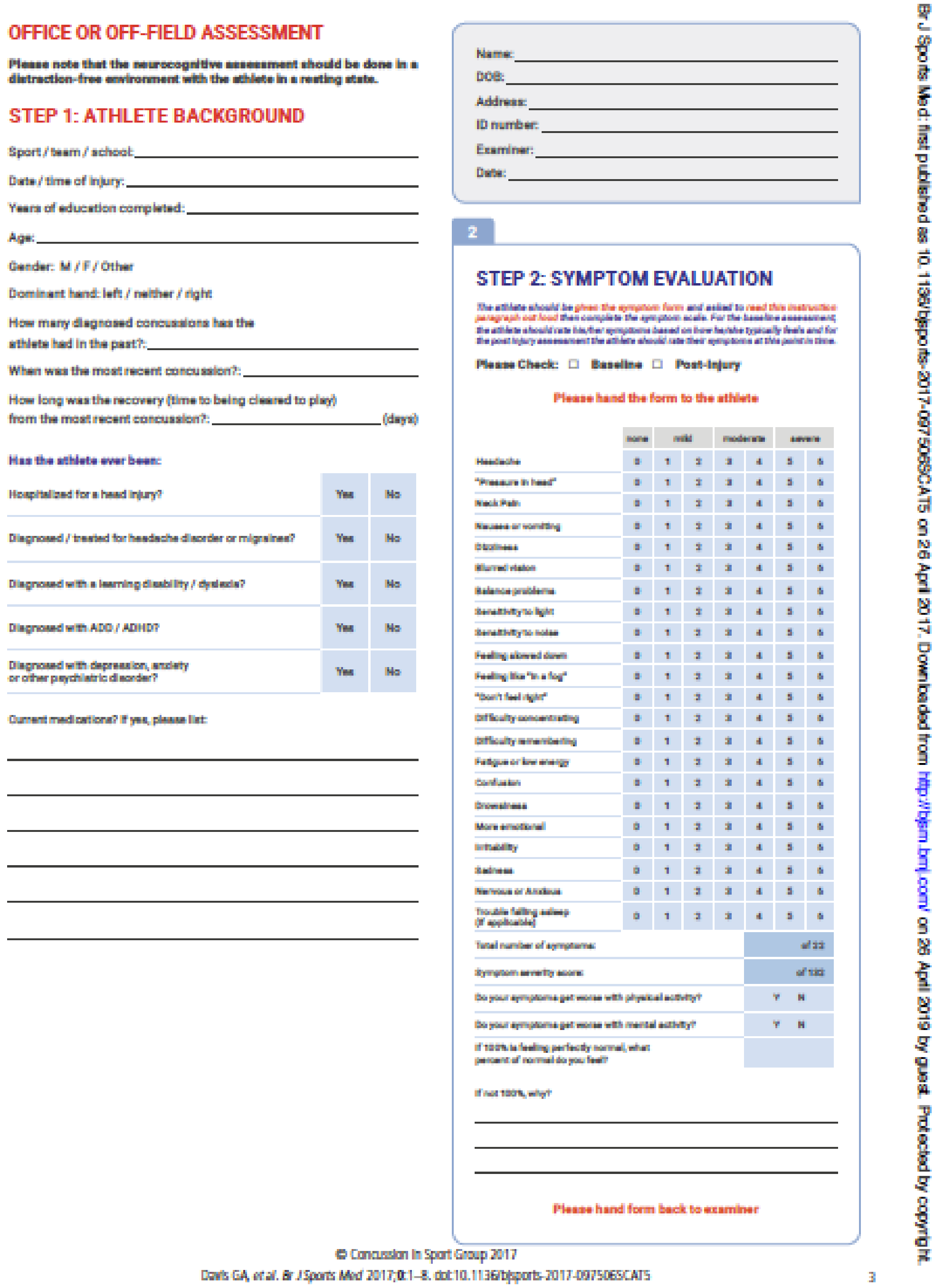
APPENDIX A

SUPPLEMENTARY MATERIAL



OFFICE OR OFF-FIELD ASSESSMENT

Please note that the neurocognitive assessment should be done in a distraction-free environment with the athlete in a resting state.

STEP 1: ATHLETE BACKGROUND

Sport / team / school: ____________

Date / time of injury: ____________

Years of education completed: ____________

Age: ____________

Gender: M / F / Other

Dominant hand: left / neither / right

How many diagnosed concussions has the athlete had in the past?: ____________

When was the most recent concussion?: ____________

How long was the recovery (time to being cleared to play) from the most recent concussion?: ____________ (days)

Has the athlete ever been:

Hospitalized for a head injury?	Yes	No
Diagnosed / treated for headache disorder or migraines?	Yes	No
Diagnosed with a learning disability / dyslexia?	Yes	No
Diagnosed with ADD / ADHD?	Yes	No
Diagnosed with depression, anxiety or other psychiatric disorder?	Yes	No

Current medications? If yes, please list:

____

Name: ____________

DOB: ____________

Address: ____________

ID number: ____________

Examiner: ____________

Date: ____________

2

STEP 2: SYMPTOM EVALUATION

The athlete should be given the symptom form and asked to read this instruction paragraph out loud then complete the symptom scale. For the baseline assessment, the athlete should rate his/her symptoms based on how he/she typically feels and for the post injury assessment the athlete should rate their symptoms at this point in time.

Please Check: ☐ **Baseline** ☐ **Post-Injury**

Please hand the form to the athlete

	none	mild		moderate		severe	
Headache	0	1	2	3	4	5	6
"Pressure in head"	0	1	2	3	4	5	6
Neck Pain	0	1	2	3	4	5	6
Nausea or vomiting	0	1	2	3	4	5	6
Dizziness	0	1	2	3	4	5	6
Blurred vision	0	1	2	3	4	5	6
Balance problems	0	1	2	3	4	5	6
Sensitivity to light	0	1	2	3	4	5	6
Sensitivity to noise	0	1	2	3	4	5	6
Feeling slowed down	0	1	2	3	4	5	6
Feeling like "in a fog"	0	1	2	3	4	5	6
"Don't feel right"	0	1	2	3	4	5	6
Difficulty concentrating	0	1	2	3	4	5	6
Difficulty remembering	0	1	2	3	4	5	6
Fatigue or low energy	0	1	2	3	4	5	6
Confusion	0	1	2	3	4	5	6
Drowsiness	0	1	2	3	4	5	6
More emotional	0	1	2	3	4	5	6
Irritability	0	1	2	3	4	5	6
Sadness	0	1	2	3	4	5	6
Nervous or Anxious	0	1	2	3	4	5	6
Trouble falling asleep (if applicable)	0	1	2	3	4	5	6

Total number of symptoms:	of 22
Symptom severity score:	of 132
Do your symptoms get worse with physical activity?	Y N
Do your symptoms get worse with mental activity?	Y N
If 100% is feeling perfectly normal, what percent of normal do you feel?	

If not 100%, why?

____

Please hand form back to examiner

Supplementary Figure 1. Sport Concussion Assessment Tool – 5th Edition symptoms inventory.

Godin Leisure-Time Exercise Questionnaire

During a typical **7-Day period** (a week), how many times on the average do you do the following kinds of exercise for **more than 15 minutes** during your free time (write on each line the appropriate number).

Weekly leisure activity score = (9 × Strenuous) + (5 × Moderate) + (3 × Light)

	Times per week		Totals
a) **STRENUOUS EXERCISE (HEART BEATS RAPIDLY)** (e.g., running, jogging, hockey, football, soccer, squash, basketball, cross country skiing, judo, roller skating, vigorous swimming, vigorous long distance bicycling)		**X9**	
b) **MODERATE EXERCISE (NOT EXHAUSTING)** (e.g., fast walking, baseball, tennis, easy bicycling, volleyball, badminton, easy swimming, alpine skiing, popular and folk dancing)		**X5**	
c) **MILD/LIGHT EXERCISE (MINIMAL EFFORT)** (e.g., yoga, archery, fishing from river bank, bowling, horseshoes, golf, snow-mobiling, easy walking)		**X3**	
WEEKLY LEISURE-TIME ACTIVITY SCORE			

EXAMPLE
Strenuous = **3** times/wk
Moderate = **6** times/wk
Light = **14** times/wk
Total leisure activity score = (9 × **3**) + (5 × **6**) + (3 × **14**) = 27 + 30 + 42 = 99

Godin Scale Score	**Interpretation**
24 units or more	Active
14 – 23 units	Moderately Active
Less than 14 units	Insufficiently Active/Sedentary

Adapted from: Godin, G. (2011). The Godin-Shephard leisure-time physical activity questionnaire. Health & Fitness Journal of Canada, 4(1), 18-22.

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Supplementary Figure 2. Godin Leisure Time Exercise Questionnaire.

CONCUSSION HISTORY									
	Mechanism	The concussion was diagnosed or undiagnosed	Approximate date of injury (mm/yyyy)	Age at time of injury	Did you lose consciousness (i.e. knocked out/blacked out)?	How long were you unconsciousness (seconds)?	Did/do you have difficulty remembering things before or after the injury?	How many minutes do you not remember (min)	How many days did you experience symptoms related to the injury?
Injury #1	☐ Blow to head or neck ☐ Motor vehicle crash - pedestrian/ bicyclist ☐ Motor vehicle crash occupant ☐ Sport / recreation ☐ Fall ☐ Fight or being hit ☐ Explosion / Blast ☐ Other	☐ Diagnosed ☐ Undiagnosed	____/_____		☐Yes ☐No	________(sec) ☐ Unknown	☐Yes ☐No	_______(min) ☐ Unknown	________(days) ☐ Unknown
Injury #2	☐ Blow to head or neck ☐ Motor vehicle crash - pedestrian/ bicyclist ☐ Motor vehicle crash occupant ☐ Sport / recreation ☐ Fall ☐ Fight or being hit ☐ Explosion / Blast ☐ Other	☐ Diagnosed ☐ Undiagnosed	____/_____		☐Yes ☐No	________(sec) ☐ Unknown	☐Yes ☐No	_______(min) ☐ Unknown	________(days) ☐ Unknown

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Supplementary Figure 3. Michigan TBI identification method form. National Institute of Health common data element form of concussion reporting. Additional injury rows may be added if necessary.