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FUNCTIONAL MOVEMENT DEFICITS IN RELATION TO SPORT-RELATED CONCUSSION

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A dissertation submitted to the faculty of the University of North Carolina at Chapel Hill in partial fulfillment of the requirements for the degree of Doctor of Philosophy in the Human Movement Science Curriculum in the School of Medicine.

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ABSTRACT

Robert C. Lynall: Functional Movement Deficits In Relation to Sport-Related Concussion
(Under the direction of Jason P. Mihalik)

The objective of this dissertation was to identify tandem gait dynamic balance deficits and assess dynamic functional movement in recreational athletes with and without a history of concussion within the past 18 months. We recruited a convenience sample of 30 college-aged recreational athletes. There were two groups (15 participants per group): 1) Recent concussion group (median time since concussion 126 days, range 28-432 days), and 2) Matched control group with no recent concussions. Control participants were matched to injured participants based on sex, age (±1 year), mass (±10%), and height (±5%). We measured center of pressure outcomes under 4 tandem gait (heel-to-toe walking) conditions: 1) Tandem gait (eyes open, no cognitive distraction), 2) Tandem gait, eyes closed (no cognitive distraction), 3) Tandem gait, eyes open, cognitive distraction (Brooks Visuospatial Task), and 4) Tandem gait, eyes closed, cognitive distraction (Brooks Visuospatial Task). We investigated joint kinematics and reaction time during 3 movement tasks: 1) Jump-landing, 2) Anticipated-cut, and 3) Unanticipated-cut. The recently concussed group demonstrated slower velocity during tandem gait compared to the control group (4.0 cm/s difference; $F_{1,27}$=4.26; p=0.049; ES=0.38). Greater dual-task cost was observed for center of pressure speed ($F_{3,26}$=5.13; p=0.032) such that the concussion group (23.5%) reduced their center of pressure speed to a greater extent than the control group (16.3%) during the eyes closed dual-task condition as compared to the eyes closed, no cognitive task condition. There were no between-group differences in reaction time during cutting tasks, but the control group displayed better reaction time cost (-10.7%) than the concussed group (-0.8%) during anticipated cutting ($F_{2, 25}$=5.26; p=0.030). The concussed group displayed greater trunk flexion compared to the control group during anticipated cut towards the non-dominant side (5.1° difference; $F_{2, 27}$=5.89; p=0.022; ES=0.63). There may be subtle movement differences that are detectable more than a month after return-to-activity following concussion, but the clinical meaning of these findings is unclear. Limitations include a lack of baseline data and a relatively small sample size. Longitudinal investigations should identify acute movement deficits after concussion in comparison with recovery on traditional concussion assessment tools while also recording musculoskeletal injury outcomes.

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LIST OF ABBREVIATIONS

ACL	Anterior Cruciate Ligament
ANCOVA	Analysis of covariance
BESS	Balance Error Scoring System
CI	Confidence Interval
cm	Centimeters
cm/s	Centimeters per second
COP	Center of Pressure
DT	Dual-task
DTC	Dual-task Cost
EC	Eyes Closed
ES	Effect Size
Hz	Hertz
ICC	Intraclass Correlation Coefficient
kg	Kilograms
L5	Lumbar spine level 5
m	Meters
m/s	Meters per second
n	Frequency
N	Newtons
PKMAS	Protokinetics Movement Analysis Software
RTC	Reaction Time Cost
s	Seconds
SCAT3	Sport Concussion Assessment Tool 3rd Edition
SD	Standard Deviation

SOT	Sensory Organization Test
ST	Single-task
TG	Tandem Gait
TGEC	Tandem Gait Eyes Closed
TGDT	Tandem Gait Dual-task
TGDTEC	Tandem Gait Dual-task with Eyes Closed
yrs	Years

CHAPTER I: INTRODUCTION

Failure to properly diagnose and manage concussion can result in catastrophic secondary events of severe brain injury or death after a second injury is sustained when symptoms from the initial injury have yet to fully resolve.[1] A large proportion of brain-related fatalities in football players under the age of 21 were associated with a recent history of symptomatic sport-related concussion.[2] Athletes failing to report symptoms during activity is common, and further complicates clinical management of sport-related concussion.[3] This underscores the need for more objective, clinician-friendly tests.

To that end, several validated post-injury assessments identify symptoms[4] and deficits in mental status,[5] neurocognition,[6] and static balance[7] following concussion. Over 85% of patients demonstrate full recovery within 7 days of injury as measured by symptom reports and traditional measures of neurocognition and static balance deficits following concussion.[8] At this point in the patient's recovery, athletes are often guided back to full return-to-participation over the course of several days. When accounting for this gradual return-to-participation structure, the majority of athletes will return to full participation within 10-15 days of the brain injury.

Several investigations have called into question the validity of labeling an athlete as 'recovered' based solely upon symptom, neurocognitive, and static balance measures. Athletes who have suffered an initial concussion are 3 to 6 times more likely to suffer a subsequent concussion.[9, 10] Additionally, of 12 same-season repeat concussions that occurred during one prospective investigation, 11 occurred within 10 days of the initial injury even though the athletes had recovered on measures of symptom reporting, neurocognition, and static balance.[9] Further, research has demonstrated athletes are at an increased risk for musculoskeletal injury following return-to-participation after concussion.[11-14] These findings suggest there may be lingering motor control deficits remaining well after the clinical recovery one can measure with current assessment tools, which may increase the risk of subsequent neurological and musculoskeletal injury. While several studies have reported similar outcomes in regards to musculoskeletal injury risk following concussion, limitations to these works exist. Importantly, none of these investigations observed other factors that may influence injury risk following concussion, such as overall exposure to injury and behavioral risk and care taking profiles of individual athletes.

The increased risk for musculoskeletal injury may not be surprising given the existing literature detailing deficits in standard gait following concussion, both acutely[15, 16] and persisting beyond return-to-play.[17, 18] Considering these documented gait deficits, such as loss of dynamic balance control[75] and conservative adaptions,[56] and the increased musculoskeletal injury risk, it is surprising that functional movement assessments are not performed following suspected concussion. This may be due to the small dynamic balance differences observed in laboratory settings, which may not translate to clinically observable outcomes, or to the large movement variance observed between individuals. A functional movement assessment may have clinical utility as both a diagnostic tool and a mechanism by which return-to-participation can be safely evaluated and monitored.

A tandem gait task with a recorded time component has been suggested as a valid, cost-effective, and clinician friendly means of objectively identifying post-concussive deficits.[19] Unfortunately, the tandem gait task included in the Sport Concussion Assessment Tool-3rd Edition (SCAT3)[19] was created without any scientific validity or evidence of how concussion affects tandem gait. This tandem gait task bases patient pass or fail on a single variable (time to task completion). In the SCAT3 tandem gait test, the patient completes 4 total tandem gait trials, with the shortest time considered as the scored trial. If the time to task completion exceeds 14 seconds, the patient is said to have failed the tandem gait task. No consideration is given to trials in which the patient is unable to maintain balance throughout the trial. In fact, the SCAT3 recommends re-starting the trial in cases where the patient is unable to maintain balance while walking along a straight line. Based on this single pass/fail criterion, 80% of healthy high school athletes fail the tandem gait task.[20] This lack of clinical specificity is unacceptable. More information is needed so an effective test of functional movement can be incorporated into clinical athletic training. Additionally, increasing neuromechanical constraints by adding a cognitive distractor task during tandem gait (dual-task) may further challenge the ability of the patient to maintain neuromuscular control. This dual-task paradigm, used previously to investigate standard gait deficits following concussion,[15, 16, 18] seeks to challenge the patient in the same way athletic participation will challenge them as they return to sport activity.

Functional deficits noted post-concussion may be related to disrupted cortical pathways. Using transcranial magnetic stimulation to assess cortical hypoexcitability following concussion, researchers have demonstrated lower intra-cortical facilitation,[21] lower maximal voluntary muscle activation,[21] increased motor evoked potential latency, and decreased motor evoked potential amplitude.[22, 23] These results suggest the brain's ability to control movement may be impaired, both acutely and after return-to-participation, following concussion. Further, small changes in cortical response to external stimuli may be exacerbated in highly dynamic environments. For this reason, it is important to explore potential movement differences between concussed and healthy individuals in a dynamic, sport-like setting.

It is possible deficits that go unaccounted for, such as processing speed and reaction time, may influence functional movement, resulting in measurable biomechanical deficits following concussion. Further investigation is needed to identify specific biomechanical deficits during sport-like functional movements that may be present in athletes post-concussion. It is unlikely a standard gait task alone will be in-depth enough to understand all biomechanical maladaptations that may occur after brain injury. Identifying lower extremity biomechanics that may increase injury risk and potential functional reaction time deficits present during sport-specific activities will inform the mechanisms underlying the increased risk of musculoskeletal injury following concussion. This may enhance rehabilitation protocols following concussion to combat the biomechanical maladaptations leading to lower extremity musculoskeletal injuries.

The overall objective of this dissertation was to identify tandem gait dynamic balance deficits and assess dynamic functional movement in recently concussed recreational athletes (within the past 18 months), relative to comparison subjects with no concussion within the past 18 months. Our central hypothesis was that sport-related concussion would result in dynamic balance deficits during tandem gait that are still identifiable after the athlete has returned to play due to lingering motor control and dynamic functional movement deficits from the injury that are not assessed using conventional concussion assessment tools. Identifying lingering concussion deficits may lead to safer and more effective return-to-participation strategies, which could help decrease potential long-term deficits associated with concussion.

Specific Aims & Research Hypotheses

Specific Aim 1. ***Determine differences in tandem gait dynamic balance between concussed recreational athletes and non-concussed control participants.***

Hypothesis 1A. Due to lingering neuromuscular control maladaptations from concussion, recently concussed recreational athletes will demonstrate worse dynamic balance (increased center of pressure path, decreased center of pressure speed and velocity) during tandem gait as compared to controls who were not recently concussed.

Hypothesis 1B. Previous research has demonstrated observable group differences during dual-task conditions during standard gait. Diminished attentional capacity may negatively affect previously concussed individuals' ability to perform simultaneous gait and cognitive tasks. Thus, we hypothesize recently concussed recreational athletes will demonstrate greater dual-task cost (center of pressure path, speed, velocity, and cognitive component) as compared to controls who were not recently concussed during the tandem gait dual-task conditions.

Hypothesis 1C. Due to lingering neuromuscular control maladaptations from concussion, we hypothesize dynamic balance outcomes (center of pressure path, speed, and velocity) will worsen as condition difficulty increases (in order: tandem gait, tandem gait with eyes closed, tandem gait with Brooks Visuospatial Task, tandem gait with eyes closed and Brooks Visuospatial Task). Additionally, we hypothesize there will be a significant group by condition interaction, such that the recently concussed group will perform significantly worse than the control group as the conditions increase in difficulty.

<u>Specific Aim 2.</u> Identify functional movement and dynamic balance differences that present following traditional return to full participation after concussion in recreational athletes and non-concussed control participants.

Hypothesis 2A: Reaction time is affected after concussion and is only assessed in a static environment. These reaction time deficits may take longer to resolve when assessed during dynamic movement tasks such as those athletes experience during sport. We hypothesize recently concussed recreational athletes will demonstrate slower movement reaction times and greater reaction time cost during anticipated and unanticipated cutting tasks as compared to healthy matched controls when reaction time is assessed in a more dynamic, sport-like environment.

Hypothesis 2B: Subtle motor cortex deficiencies (increased motor evoked potential latency, decreased motor evoked potential amplitude) following concussion may cause slight joint kinematic alterations after traditional recovery from the brain injury, possibly contributing to increased risk of musculoskeletal injury. Thus, we hypothesize recently concussed recreational athletes will demonstrate biomechanical risk factors for lower extremity injury (increased knee adduction angle and trunk flexion angle at initial ground contact, decreased knee flexion angle at initial ground contact) as compared to healthy matched controls.

Hypothesis 2C: Measures of static balance recover within 3-5 days following concussion, but reports of dynamic balance during gait suggest balance differences between concussed and healthy participants, even after static balance has recovered. If dynamic balance assessments are more sensitive to lingering balance control deficits, we hypothesize recently concussed recreational athletes will demonstrate decreased dynamic balance control (increased center of pressure speed and path and increased time to stabilization) as compared to controls who were not recently concussed.

Hypothesis 2D: Beyond movement, joint proprioception may play an important role in musculoskeletal injury risk. Persistent motor cortex alterations following concussion may decrease joint proprioception. Thus, we hypothesize recently concussed recreational athletes will demonstrate decreased proprioception (larger absolute error across trials in joint position sense) as compared to healthy matched controls.

CHAPTER II: LITERATURE REVIEW

Introduction

Many effective concussion assessment and management tools have been developed and described in the literature.[5, 7, 19, 24] Despite widespread clinical use of various tools,[25] current return-to-participation assessment lacks investigation of functional movement. This may be an important missing component to concussion evaluation, as increased rates of musculoskeletal injury[12-14, 26] along with dynamic balance and spatiotemporal deficits during gait following concussion have been identified.[15, 27, 28] Despite this knowledge, there is no agreed upon assessment of functional movement after concussion. Standard gait dynamic balance deficits such as increased medial-lateral center of mass displacement and reduced velocity have been identified under sophisticated laboratory conditions. Unfortunately, very few clinicians have access to this technology. This, among other factors, is likely a key reason why functional movement assessments have not been recommended for clinical practice.

Tandem gait has been proposed as a method to identify dynamic balance deficits following concussion.[19] However, based on a single pass/fail criterion (time to task completion of 14 seconds), 80% of healthy high school athletes fail the tandem gait task.[20] Thus, this dissertation aims to identify specific dynamic balance deficits during tandem gait following concussion. This knowledge is an important first step in translating functional movement assessment from the laboratory to the clinic. Beyond gait, understanding how athletes move after concussion in a dynamic, sport-like environment will help inform our understanding of the increased rates of lower extremity musculoskeletal injury.[14]

Concussion Assessment Battery

Due to the complex nature of concussion, which has the potential to result in a wide range of post-injury deficits, multiple position and consensus statements call for a multi-faceted approach to concussion diagnosis and management.[19, 29] At a minimum, this assessment battery should include objective tests of balance, neurocognition or neurological status, and symptoms. It is important to include assessments in each of these domains because recovery in one domain does not always translate to recovery in one or more of the other domains.[30] Over the last 2 decades, several clinician-friendly (easy to apply, accurate, and low cost) objective measures have been developed and validated for use in concussion diagnosis and management. These assessments have been created in response to known impairments following concussion.

Static Balance Deficits Following Concussion

The maintenance of postural control is a complex process involving brain integration and control of afferent and efferent nervous system pathways. Essential afferent information is provided to the brain from cutaneous receptors, in addition to somatosensory, visual, and vestibular inputs. Under normal conditions, inputs from cutaneous receptors in the foot along with visual and somatosensory information are adequate to maintain the center of gravity within the body's base of support.[31] The role of the vestibular system is emphasized in cases where there is disruption or conflicting information from one or more of the aforementioned systems. Deficits in postural control following concussion have been mainly attributed to sensory integration issues.[31] In cases where input from one of the postural control systems is manipulated, such as a moving visual surround or support surface, concussed individuals demonstrate increased measures of postural sway (i.e. worse postural control) compared to their own baseline scores as well as to healthy controls.[32] Healthy subjects are able to effectively identify and ignore distracting input from altered environmental conditions. For example, under false visual conditions (visual reference moves in phase with subject's center of pressure), a healthy individual is able to adapt by identifying and ignoring this false visual input and instead rely on somatosensory and/or vestibular information to maintain balance. Therefore, it is hypothesized concussed individuals suffer from an inability to ignore altered environmental conditions, causing them to select a motor response based on these altered cues.[31-33]

Postural control deficits following concussion have been demonstrated using both sophisticated laboratory measures and less expensive clinician-friendly methods.[7] The Sensory Organization Test (SOT), performed on a force plate system called the NeuroCom Smart Balance Master (Clackamas, OR), allows for the manipulation of visual and/or somatosensory input during quiet stance. Investigations of post-concussion postural stability deficits utilizing the SOT have demonstrated increased postural sway for up to 3 days following the injury.[32-34] These findings have been repeated with a more clinically feasible test known as the Balance Error Scoring System (BESS).[4, 32, 34] The BESS consists of 6 total trials utilizing 3 stances (feet together, single leg, and tandem stance) and 2 surface conditions (stable and unstable). Importantly, this test employs no expensive force plate systems while still delivering an objective outcome score based on an error scoring system that has been validated against force plate measures.[7, 32, 34]

Neurocognitive Deficits Following Concussion

Neurocognitive testing following concussion, once labeled as "one of the cornerstones of concussion management,"[35] can yield valuable objective information. Although cognitive recovery may overlap with symptom recovery, it is possible the 2 may be independent of each other.[36-38] Neurocognitive deficits have been identified following concussion utilizing both traditional paper and pencil tests[39] as well as computerized testing platforms.[40, 41]

Concussed participants have demonstrated deficits in several neurocognitive domains, including verbal and visual memory[42, 43] and reaction time.[44] Importantly, these deficits have been shown to linger beyond the usual recovery of static balance and symptom deficits.[37, 45] This underscores the need to investigate all possible deficits following concussion.

Symptom Deficits Following Concussion

Self-reported symptom assessments are one of the most common means of diagnosing concussion.[25] While specific symptoms of concussion vary widely after each injury, common symptoms include headache, dizziness, loss of memory, visual disturbances, and feeling “in a fog.” The number of symptoms and the severity of each are generally recorded following injury. Symptom recovery appears to differ between athletes of different ages. For college-aged athletes, concussion symptoms commonly recover between 5 and 10 days for the majority of injured subjects.[4, 39, 46] Evidence suggests younger athletes may take longer to recover from concussion and this recovery time may be lengthier in those suffering from a previous history of concussion. Amongst a cohort of high-school aged subjects suffering from their first concussion, the median time to symptom recovery was 12 days. Amongst those who had suffered more than 1 previous concussion, median time to symptom resolution was 28 days.[47] These differences in concussion recovery, among others, underscore the need for a complete and thorough assessment battery that accounts for all possible post-injury deficits.

Tandem Gait Assessment Following Concussion

In response to known static balance deficits and increasing evidence of functional movement deficits following concussion, a consensus panel of concussion experts from around the world have advocated for the addition of a tandem gait task to sideline concussion management protocols.[19] This tandem gait task consists of 4 trials of heel-to-toe walking along a 3-meter long straight line. The participant keeps his or her eyes open throughout the trial without being given direction as to the placement of the hands. Each trial is timed and the shortest time to complete the task is recorded and considered to be the scored trial. Trials lasting longer than 14 seconds are deemed failed trials. If at any time the subject is unable to maintain balance while walking, the trial is stopped and re-started. This tandem gait task was based on 2 published articles investigating normative values for a wide age range of participants (16-37 years)[48] and surface/footwear interactions that may affect test outcomes.[49] Importantly, no studies to date have investigated the effect of concussion on tandem gait outcomes. One study observed 80% of healthy high school aged athletes take longer than 14 seconds to complete the tandem gait task and, thus, are considered to have failed the tandem gait test in a healthy state.[20] In order for a more sensitive and specific tandem gait task to be developed, much more understanding is needed of how concussion affects tandem gait dynamic balance outcome variables.

Impairments in Gait Following Concussion

Variables of Interest in Gait Studies

Many gait variables have been explored to study deficits following concussion. These variables can be group into 2 categories: spatiotemporal variables and dynamic balance variables. Spatiotemporal variables are those outcome measures that are defined by time and/or distance. Dynamic balance variables are those outcome measures that attempt to quantify sway through various means during gait. Although these variables are not standard across all published research, in most cases between-study differences in defining these variables are negligible. **Tables 1** and **2** display the most common calculations of some variables of interest in the concussion gait literature.

Exploring both spatiotemporal and dynamic balance variables allows for an assessment of 2 key underlying mechanisms of gait following concussion: a possible conservative adaptation (spatiotemporal) and the likelihood of balance loss (dynamic balance). Even though many of the spatiotemporal and dynamic balance variables are reported in the same studies, it is worth noting several of them are interrelated. For example, a person displaying more conservative gait is likely to reduce stride time and decrease stride length. These reductions will likely result in a decrease in any number of anterior/posterior dynamic balance variables during standard gait, including velocity, range of motion, and displacement. While this is the most intuitive association between the variables, spatiotemporal variables will not always change in the same manner. Stride time could decrease while stride length increases, resulting in no detectable change in the dynamic balance variables. For this reason, dynamic balance variables in the sagittal plane are usually thought to be conservative adaptions in gait as opposed to balance loss.[50] Dynamic balance measures in the frontal plane, along with several frontal plane spatiotemporal variables, likely give the best insights into postural control during gait. Center of mass range of motion and maximum separation of the center of mass and center of pressure (both in the frontal plane) are correlated with stride width.[50] Frontal plane center of mass measures of velocity do not necessarily relate to any spatiotemporal variables, but have been shown to be an important variable to describe imbalance in the frontal plane during gait following concussion.[51] Many measures have been studied and are found throughout the concussion gait literature. Due to the disparity in outcomes reported in the concussion literature, there is no way to identify one or some of these variables as superior. Further, no investigations have explored a concussed sample during tandem gait.

The Single-Task Paradigm in Gait Studies Following Concussion

The study of gait following concussion under single-task conditions during level walking has only revealed minimal group differences (concussed vs. healthy controls). From a spatiotemporal perspective, gait velocity appears to be the most sensitive variable,[16, 17, 28] although increased stride time in concussed individuals has been noted as well.[16] Differences in several dynamic balance variables are also present, including decreased frontal plane range of motion,[15] sagittal plane separation between center of mass and center of pressure,[17] and sagittal plane center of mass velocity.[28] These differences, however, are only present within 48 hours of injury. When the concussed individual moves to the 5th day post-injury and beyond, differences in single-task performance on both spatiotemporal and dynamic balance variables disappear. Together, these acute differences likely point to the adoption of a more conservative gait strategy following concussion.

The Dual-Task Paradigm in Gait Studies Following Concussion

The classic version of the dual-task paradigm explores 2 tasks simultaneously, with one of the tasks designated as primary.[52] These tasks, one of which is typically cognitive based while the other motor based, compete for the subject's attentional demands. Baseline measures are taken of both tasks performed in isolation (single-task) to establish normal values for that participant. If under dual-task conditions the secondary task performance drops, it is suggested the participant had insufficient attentional reserve to maintain the secondary task at the baseline level.[53]

In this classic dual-task paradigm, it is imperative primary task performance is maintained. Because this is difficult in a laboratory setting, researchers have found additional ways to assess performance under dual-task conditions. Instead of designating a primary and secondary task, participants perform both tasks simultaneously without being instructed to direct their focus to either. This method of dual-task investigation is very clinically applicable as most real-world scenarios call for some degree of split attention (dual-task) throughout the day. Multiple outcomes are possible when dual-task conditions are investigated. Performance in the motor task could increase or decrease with or without a corresponding change in cognitive performance.[52, 54]

In order to measure decreased performance of the cognitive and/or motor task under dual-task conditions, relative dual-task cost is employed. The simple dual-task cost (DTC) formula that follows accounts for baseline differences in the single-task (ST) condition, allowing for meaningful comparisons to be made within participants and between groups:

$$DTC = [(DT - ST) / ST] \times 100$$

This cost, represented as a percentage, can certainly be influenced by task priority. Generally speaking, the task with the greatest dual-task cost is thought to be the secondary task, although this can also be influenced by task difficulty.[52]

Several different cognitive tasks have been used in conjunction with a motor task in the concussion gait literature. The most commonly employed cognitive task is the Modified Mental Status Examination, which consists of a series of simple mental tasks.[16, 17, 50] These tasks include spelling common 5-letter words in reverse, counting backwards by sevens, or reciting the months of the year in reverse order. Other cognitive tasks have been reported as well, including a simple reaction time task,[16] auditory or visual Stroop Task,[55-57] and the Brooks Visuospatial Task.[18] Howell et al. investigated the effect of dual-task complexity on gait stability following concussion in adolescents.[27] The authors reported increased cognitive task complexity has a greater effect on gait balance control. This is important, especially when attempting to identify lingering gait deficits after concussed individuals have returned to full sport participation. Employing the most challenging dual-task protocol may allow researchers and clinicians to better identify lingering deficits during functional movement.

To that end, we have used the Brooks Visuospatial Task during pilot testing. The Brooks Visuospatial Task is designed to tax the visuospatial component of cognition.[18] Previous research has established an important connection between cognition and motor function.[12, 13] It has been speculated these associations exist because cognition and motor function rely on the same neural network.[57] Sosnoff et al. explored this association in concussed individuals.[58] They reported cognitive/motor function associations were present after concussion, but not before. In this investigation, cognition and motor function were tested independently (i.e. not under dual-task conditions). Significant associations were found between several cognitive outcomes (simple and complex reaction time, verbal and visual memory) and both an overall composite balance score and a visual ratio balance score. This indicates these deficits are not necessarily due to a decreased pool of attentional resources, but may be due to deficits within a shared process, such as visuospatial attention.[58] Thus, because the Brooks Visuospatial Task taxes the visuospatial component of cognition, it has the potential to exacerbate cognitive and motor deficits observed after concussion. Additionally, the Brooks Visuospatial Task is very challenging. For example, **Figure 1** illustrates the effect of various tandem gait conditions on gait velocity in a small cohort (n=9) of healthy college-aged individuals walking across a 14-foot gait mat. Differences in gait velocity during tandem gait with eyes closed and the Brooks Visuospatial Task as compared to tandem gait alone and tandem gait with eyes closed were observed, suggesting increasing task complexity with the Brooks Visuospatial Task. These pilot data helped inform hypothesis 1C, that there would be an interaction between concussion (group) and tandem gait condition. This paradigm with increasing difficulty is ideal, as we investigated concussed individuals after they were cleared to fully return to sport participation.

Both spatiotemporal and dynamic balance deficits have been observed during gait under dual-task conditions following concussion. In contrast to the acute single task deficits, dual-task deficits are present at both acute time points[15-17, 28, 50, 56, 59] and beyond athlete return-to-participation.[17, 18, 50, 59] Not only do these deficits suggest dual-task gait paradigms are more sensitive to concussion, it also implies deficits persist long after the injured athlete is believed to have fully recovered based on common clinical measures of concussion. When group comparisons are considered acutely under dual-task conditions, concussed subjects appear to adopt a more conservative gait strategy by decreasing stride length[15, 17] and velocity[16, 17, 28] along with decreasing sagittal plane center of mass velocity.[16, 28, 50, 56] Additionally, concussed subjects appear to walk with diminished postural control as compared to controls under dual-task conditions. The lack of postural control is evident by increased frontal plane center of mass range of motion,[15, 16, 28] frontal plane separation between center of mass and center of pressure,[17] and frontal plane center of mass velocity.[16]

At time points beyond the average return-to-participation timeframe, group differences persist when the dual-task paradigm is employed. It appears concussed subjects continue to display a more conservative gait strategy as evidenced by decreased stride length at the 14 day post-injury time point and decreased separation between center of mass and center of pressure in the sagittal plane at both 14 and 28 days following injury.[17] Interestingly, there is evidence of gait deficits persisting in a cohort of previously concussed individuals who were, on average, over 6 years post-injury. This cohort demonstrated increased double leg stance time along with decreased single leg stance time and velocity.[18]

While all of the findings discussed thus far have emerged from studies employing similar college-aged cohort methodology, it is worth discussing that several other studies have employed different methodologies to achieve the same end. Dual-task cost has been discussed as a potentially important variable of interest in the study of gait following concussion. Dual-task cost related to gait speed has been shown to be sensitive to group differences in a college-aged cohort. These differences were present in multiple dual-task conditions as well as obstacle avoidance conditions in which the participants had to step over an obstacle.[60] Group differences during obstacle avoidance tasks are intriguing findings. Avoiding an obstacle may increase postural control demands on the neuromuscular system, not unlike athletic participation. Further exploration of dynamic balance variables under obstacle avoidance conditions is warranted and may further inform deficits following concussion, especially as it relates to the body's ability to dynamically control posture.

High-school aged cohort studies have also revealed group differences. One study reported dual-task cost outcomes in a cohort of high school aged participants.[61] Across the 2-month testing period, previously concussed participants demonstrated a greater dual-task cost for average walking speed, sagittal plane center of mass velocity, and frontal plane separation between center of mass and center of pressure. Importantly, the authors of this study also report concussed participants were significantly less accurate on the concurrent cognitive task as compared to matched controls. Dual-task group differences in dynamic balance variables along with a decline in cognitive task performance have also been noted in a high-school aged cohort for up to 2 months following injury.[27] Additionally, dynamic balance outcome variables have been shown to regress between pre- and post-return-to-participation following concussion in high-school aged athletes during dual-task gait conditions.[62]

It is important to recognize limitations to the study of gait following concussion. None of the reported studies have collected baseline (pre-concussion) data. Thus, it is possible reported dynamic balance group differences were present prior to the concussion. Additionally, authors have not clearly defined the clinical significance of their findings. Do these dynamic balance group differences result in higher risk of subsequent concussion and musculoskeletal injury? Do the group differences indicate unresolved brain damage that could have short- or long-term effects on quality of life? These are important questions that remain despite an increasing interest in gait related outcomes following concussion. Prospective longitudinal studies that address these outcomes will be important to better interpret the clinical implications of this body of research. Beyond simple gait tasks, more challenging and sport-specific tasks may further elucidate the significance of lingering dynamic balance deficits following return to full activity. Understanding the effect of concussion on tandem gait dynamic balance outcomes and functional movement is important to begin to build clinical assessment paradigms. Despite the cross-sectional nature of the current study, developing methods to study outcomes that may have future clinical relevance is important and has the potential to make a substantial contribution to the existing literature and knowledge base.

It is clear dual-task paradigms are more sensitive to gait deficits following concussion, but the underlying reason for this is not entirely understood. Generally, there are several theories that attempt to identify the underlying mechanism for dual-task interference. The bottleneck theory suggests only a single processing operation can happen at any given time.[63] If two tasks compete for the same processing mechanism, a bottleneck results and one or both of the tasks will be affected. A separate but related hypothesis suggests a capacity sharing of information processing.[64] As opposed to the bottleneck theory, capacity sharing suggests capacity for a given task is reduced when another task is attempted simultaneously.[63, 64] In this situation, both tasks may be performed, but each task may be affected by the other. Quantifying the effect of one task on another is an important consideration in dual-task paradigms.[54] It is imperative dual-task paradigms include both cognitive and motor task outcome measures in order to appropriately explain the observed dual-task interference.[65] In the capacity sharing model, insufficient attentional capacity to efficiently divide attention between the cognitive and motor task may affect outcomes.[66] For example, if a given participant has a fear of falling during a gait or balance task, he or she may devote the majority of their attentional capacity to the motor task. Thus, cognitive performance may suffer while motor performance remains steady. In this case, we could interpret this interference as motor-related cognitive interference, meaning motor task performance remained steady with a subsequent drop in cognitive performance.[54] Without appropriate measure of both cognitive and motor task performance, this effect may be missed completely or misinterpreted.

Further work with concussed individuals has sought to explain the mechanism underlying dual-task interference, specifically the ability of concussed individuals to maintain and switch attention between tasks. Using the Attentional Network Task, researchers have demonstrated specific attention deficits following concussion.[67] It appears the alerting component of attention is unaffected by concussion, but the executive, and to a larger extent, the orienting components of attention are affected. Briefly, the alerting component of attention is associated with the ability to maintain vigilance during continuous task performance. The executive component allows for appropriate conflict resolution while the orienting component allows for efficient selection of information based on sensory input.[68]

These findings are interesting when taken in context with dual-task gait deficits following concussion. The deficits in the orienting component of attention suggest an impaired ability to move attention from a central focus point. Additionally, the executive component deficits suggest those who have suffered a concussion are less able to appropriately ignore irrelevant or contradictory information. Adding a cognitive task to a relatively simple motor task, such as standard gait, affects both the orienting and executive components of attention, suggesting a potential mechanism behind the noted standard gait deficits in dual-task conditions.

Functional Movement Following Concussion

As discussed previously, athletes undergo a concussion assessment battery prior to full return-to-participation following concussion. While this battery is effective in identifying lingering static balance, neurocognitive, and symptom deficits, functional movement deficits go completely ignored. This is problematic given the presence of long-term gait deficits under dual-task conditions.[17, 18, 50, 59] Additionally, increased risk of subsequent concussion[9, 10] along with increased risk of musculoskeletal injury following the initial concussion[11-14] suggests an incomplete recovery. It is also possible that athletes are fully recovered from concussion, but other factors such as inherent behavioral differences (i.e. risk taking) and injury exposure may be driving reported musculoskeletal injury group differences. **Table 3** details the current literature reporting musculoskeletal injury risk after concussion. Although evidence of an association between concussion and musculoskeletal injury is growing in the literature, it is important to acknowledge alternative confounders that may affect this relationship. While some of these studies account for injury exposure, it is likely exposure was different between cohorts. Playing style, injury reporting and care-seeking behaviors, and playing position are all additional confounders to the association between concussion and musculoskeletal injury. Understanding how athletes move during sport-related activities after concussion may further inform clinical best practice in patient care and lead to an increased understanding of lingering effects that contribute to increased injury rates. Further, examining reaction time in a dynamic environment, just as the athlete will experience during competition, will lead to an increased understanding of attentional contributions to movement deficits.

Reaction Time Deficits Following Concussion

Reaction time is a commonly assessed cognitive domain following concussion that has been shown to be sensitive to injury in numerous investigations.[36, 41, 69-71] In addition to computerized and paper-and-pencil reaction time tests, a more functional reaction time test has been developed for efficient sideline use.[24] This clinical reaction time measure involves inexpensive components that are easily administered and highly portable and has been shown to be valid, reliable, and sensitive to concussion.[24, 72, 73] Briefly, this clinical reaction time measure involves a stick marked every centimeter attached to a heavy cylinder, such as a hockey puck. The clinician holds the stick such that the hockey puck is level with the subject's hand. The clinician then drops the stick at various time intervals while the subject attempts to catch it as quickly as possible. Eight total trials are performed, and the distance scores are input into a formula that converts the subject's score to a reaction time measure. As reaction time is essential not only to sport performance but to injury prevention as well, the correlation between clinical reaction time and protective reaction time (moving the hands to protect the head from an incoming ball) has been explored. Clinical reaction time demonstrated a strong correlation to protective reaction time.[74] This finding is important as decreases in reaction time following concussion have the potential to reduce protective reaction time in a dynamic sport environment. Reaction time as measured through neurocognitive testing and simple clinical testing is clearly affected by concussion. Unfortunately, the current methods to assess reaction time are far removed and much simpler than the reaction time required to perform at a high level and protect oneself during sport. Therefore, further examination of reaction time in more dynamic and demanding situations is warranted.

At-Risk Movement Patterns

Beyond reaction time assessment, understanding biomechanical movement patterns that increase musculoskeletal injury risk following concussion may lead to a better understanding of interventional methods to reduce this injury risk. While many lower extremity injuries are possible, research into the mechanism associated with anterior cruciate ligament (ACL) injury is prevalent. Although various combinations of movement may contribute to ACL injury, increased anterior shear force at the proximal tibia appears to be the major contributor to increased ACL loading as demonstrated by several investigations utilizing cadaveric models.[75, 76] The quadriceps muscles are a major contributor to anterior shear force on the proximal end of the tibia.[77, 78] For a given quadriceps force, anterior shear force on the proximal tibia increases as knee flexion angle decreases.[79] Therefore, landing from a jump or cut with a decreased knee flexion angle may lead to increased risk of ACL injury.

Although it has not received as much attention in published literature, hip adduction may be an important contributing risk factor for ACL injury. In yet unpublished findings, Marshall et al. describe the largest prospective cohort study investigating risk factors for ACL injury.[80] Military academy cadets who demonstrated hip adduction (less than 0° hip abduction) during the initial ground contact of a jump landing displayed a higher risk ratio in regards to ACL injury than those who landed in greater than 10° of hip abduction. It is unclear whether this decreased hip abduction angle was due to a narrow landing stance or an ipsilateral hip shift, possibly due to gluteus medius weakness, but it is clear diminished hip control during a jump landing is prospectively associated with ACL injury.

Core stability and trunk control may be other factors related to increased risk of injury. Movement of the trunk in the frontal plane may lead to increased valgus stress on the knee. For instance, landing from a jump with a lateral trunk shift to the right side of the body increases the overall valgus moment placed upon the right knee. Along these lines, research has indicated that increased lateral trunk displacement following a sudden force applied to the trunk may be the best predictor of knee injury.[81] Sagittal plane trunk biomechanics may also play a role in mediating ACL injury risk. Blackburn and Padua reported increased trunk flexion is associated with increases in knee and hip flexion angles as well as a decreased risk of ACL injury.[82] In contrast, the study by Marshall et al. referenced above found increased trunk flexion (greater than 40° vs. less than 25°) to be associated with a higher prospective rate of ACL injury.[80] The authors suggest this finding reflects a landing strategy in which the participant lands with too much trunk flexion. Taken together, these results suggest there is a desired amount of trunk flexion that has the potential to mitigate ACL injury risk. These findings are important as rehabilitation and athlete-training programs may be modified to emphasize movements that are associated with decreased risk of injury.

It should be noted that many factors may play a role in mediating ACL injury risk such as sex,[83] bony anatomy,[84] and genetic predisposition.[85] These factors, for the most part, are unchangeable in a given athlete. Therefore, we will focus on potential biomechanical deficits in athletes following concussion that may be modifiable. This may allow for future interventions to affect some or all of the causes of increased rates of lower extremity musculoskeletal injury following concussion.

It is important to note that no studies have investigated the effect of concussion on injury biomechanics. This is concerning given the detailed reports of dynamic balance deficits lingering beyond athlete return to play[18, 57, 62] along with the increased risk of musculoskeletal injury following concussion.[12, 14, 26] We studied outcomes that have been associated with ACL injury risk, but these outcomes do not represent all potential maladaptations that may occur after concussion. This investigation was intended to be a preliminary attempt to quantify lower extremity functional biomechanics after concussion. Future research protocols should build on our methodology in order fully explore biomechanical outcomes after concussion.

Additional Functional Movement Assessments

While the above biomechanical variables are related to ACL injury risk, many more adaptations could occur following brain injury that may contribute to increased risk of musculoskeletal injury. Ankle sprains are the most common orthopedic injury associated with sports participation, accounting for about 25% of all injuries.[86] Measures of static postural stability are often used to diagnose and manage those with chronic ankle instability. These static measures, however, may not be sensitive enough to distinguish between functionally stable and unstable ankles. Several reports have suggested dynamic measures may be more sensitive to differences between groups. Specifically, time to stabilization appears to be a better measure of ankle stability than traditional measures of static balance.[58, 87] Briefly, time to stabilization is measured following a jump from a pre-determined height. The participant lands on a single leg and is instructed to maintain their best balance as quickly as possible following landing. The total time it takes to reach a pre-determined stable posture is described as the time to stabilization.

While the underlying mechanism for deficits in dynamic stabilization for those who display functional ankle instability has largely been attributed to afferent pathway sensorimotor deficits associated with the initial ligament injury,[88] functional deficits noted post-concussion may be more related to disrupted cortical pathways. Using transcranial magnetic stimulation to assess cortical hypoexcitability following concussion, researchers have demonstrated lower intra-cortical facilitation,[21] lower maximal voluntary muscle activation,[21] increased motor evoked potential latency, and decreased motor evoked potential amplitude.[22, 23] These results suggest the brain's ability to control movement may be impaired, both acutely and after return-to-participation, following concussion. Further, small changes in cortical response to external stimuli may be exacerbated in highly dynamic environments. For this reason, it is important to explore potential movement differences in a dynamic, sport-like setting. Beyond investigating gross biomechanical differences as proposed here, further investigation will need to be done to explore the direct effect of disrupted cortical pathways on movement. Future methodology that incorporates movement outcomes and cortical pathway outcomes will greatly inform the hypotheses proposed here.

Further, investigation of lower extremity proprioception following concussion may give additional insight into potential cortical deficits leading to increased risk of musculoskeletal injury. Joint position sense (awareness of and ability to recreate the joints position in space) is an important component to proper functional movement. Effectively repeating movements during repetitive movements, such as gait or cutting during athletics, is essential to avoid injury. Following injury to a joint, local sensory receptors in the skin, tendon/muscle, ligaments, or joint capsule that provide proprioceptive information to the central nervous system may become damaged, leading to deficits in overall joint position sense.[89, 90] Concussion is interesting in that these peripheral sensory receptors are not damaged, making it unlikely they contribute to any loss of proprioception. Importantly, the brain is essential to the organization and storage of information related to proprioception. Thus, brain injury may affect motor control that is dependent on appropriate joint position sense. To our knowledge, no one has directly measured joint position sense in a dynamic environment following concussion. Including closed kinetic chain joint position sense measurements will most simulate on-field athletic movements, further informing the potential contribution of proprioception to increased risk of acute lower extremity injury during athletics.

Measures of static balance following concussion are an important part of a comprehensive test battery. As noted, previous research into static balance deficits following concussion have shown deficits persisting for approximately 3 days following injury.[32-34] More functional assessments of balance, such as those discussed above involving gait tasks, have shown deficits persisting well beyond this 3-day time frame.[17, 18, 50, 59] Additionally, investigators have sought to determine the relationship between static and dynamic balance measures. Several published articles reveal significant, but relatively weak, relationships between the static and dynamic measures.[91-94] Despite the statistically significant correlations, clinical conclusions drawn from these data suggest static and dynamic measures of balance are not reflective of the same phenomenon. These results only underscore the need for more functional assessments of balance following concussion.

It is important to consider that the hypotheses discussed to this point may only represent one mechanism affecting movement following concussion. Other psychosocial factors such as care-seeking and risk-taking may influence lower extremity musculoskeletal injury risk following concussion. Additionally, accounting for lower extremity injury exposure and head impact exposure may be important. Future work should seek to account for these and other confounders in the context of functional movement following concussion.

The Clinical Significance of Assessing Functional Movement Following Concussion

While one prominent concussion consensus statement, the Consensus Statement on Concussion in Sport, advocates for a brief tandem gait assessment,[19] no work has been done to understand deficits that may be present under tandem gait conditions following concussion. Before an appropriate clinical test can be designed, we must explore the dynamic balance deficits that may be present in tandem gait following concussion. Therefore, the objective of this investigation is to determine if dynamic balance deficits are present in tandem gait following concussion, beyond athlete recovery and return-to-participation.

While understanding these tandem gait deficits will greatly inform our clinical management of concussion, investigation of tandem gait alone is not enough to fully understand functional movement deficits. Athletes are at an increased risk of sustaining subsequent concussions[9, 10] and lower extremity musculoskeletal injuries[11-14] following an initial concussion, suggesting the current return-to-participation battery of assessments may not be robust enough to detect all deficits following injury. Thus, we must go beyond the study of gait and assess movement that pertains directly to on-field athletic performance. Understanding differences between concussed athletes and healthy controls on various measures of functional movement is essential before strategies can be devised to combat the deficits. Not only will understanding functional movement deficits following concussion lead to future rehabilitation interventions, but it will also lead to a much more thorough understanding of concussion recovery and safe return-to-participation.

Table 1. Common spatiotemporal gait variables in the concussion gait literature

Variable	**Description**
Velocity	Divide the sum of all stride lengths by the sum of all stride times (m/s)
Stride Length	Distance between 2 successive heel strikes in the sagittal plane (m)
Stride Width	Distance between 2 successive heel strikes in the frontal plane (m)
Stride Time	Time between 2 successive heel strikes (s)
Double Support Time	Percentage of total trial spent with both feet in contact with the ground
Single Support Time	Percentage of total trial spent with one foot in contact with the ground
Total Time	The total time it takes to complete a given trial (s)
Cadence	The number of footfalls divided by total time (steps/minute)

Table 2. Common dynamic balance variables in the concussion gait literature

Variable	**Description**
Center of Mass Velocity	Maximum instantaneous linear velocities of the center of mass in the sagittal and frontal planes (m/s)
Separation between Center of Mass and Center of Pressure	Maximum separation between the center of mass and supporting foot center of pressure in the sagittal and frontal planes (m)
Center of Mass Displacement	Maximum minus minimum distance of the center of mass in the sagittal and frontal planes (m)

Table 3. Summary of literature reporting musculoskeletal injury risk following concussion.

Study	**Cohort**	**Post-Concussion Timeframe**	**Outcome** (95% Confidence Interval)
Makdissi et al.[95]	Professional Australian Football	1 competitive match	*Injury Rate Ratio* - 2.23 (0.93, 5.04)
Brooks et al.[12]	Mixed College	90 days	*Odds Ratio* - 2.48 (1.04, 5.91)
Cross et al.[13]	Professional Rugby Union	24 months	*Injury Rate Ratio* - 1.6 (1.4, 1.9)
Lynall et al.[14]	Mixed College	12 months	*Injury Rate Ratio* - Pre-conc vs. post-conc[a] = 1.97 (1.19, 3.28) - Conc vs. control = 1.64 (1.07, 2.51)
Nordstrom et al.[26]	Professional Soccer	12 months	*Hazard Ratio*[b] - 1.47 (1.05, 2.05)
Burman et al.[96]	Mixed Athlete	24 months	*Odds Ratio* - Pre Concussion[c] = 1.98 (1.45, 2.72) - Post Concussion[d] = 1.72 (1.26, 2.37)
Pietrosimone et al.[97]	Retired Professional Football	Reported history	*Odds Ratio*[e] - 1 conc vs. 0 conc = 1.59 (1.30, 1.94) - 2 conc vs. 0 conc = 2.29 (1.85, 2.83) - 3+ conc vs. 0 conc = 2.86 (2.36, 3.48)

All studies compared a concussed group to a control group, unless otherwise noted. All outcome ratios are reported as concussion/control.

[a] Compared injury rates in year post-concussion to year pre-concussion in concussion group only.

[b] Reported results are when controlling for number of injuries in the year preceding concussion.

[c] Analyzed injuries prior to concussion.

[d] Analyzed injuries after concussion.

[e] Reported odds ratios for those who had a history of 1, 2, or 3+ concussions compared to those with 0 concussions. Conc = concussion.

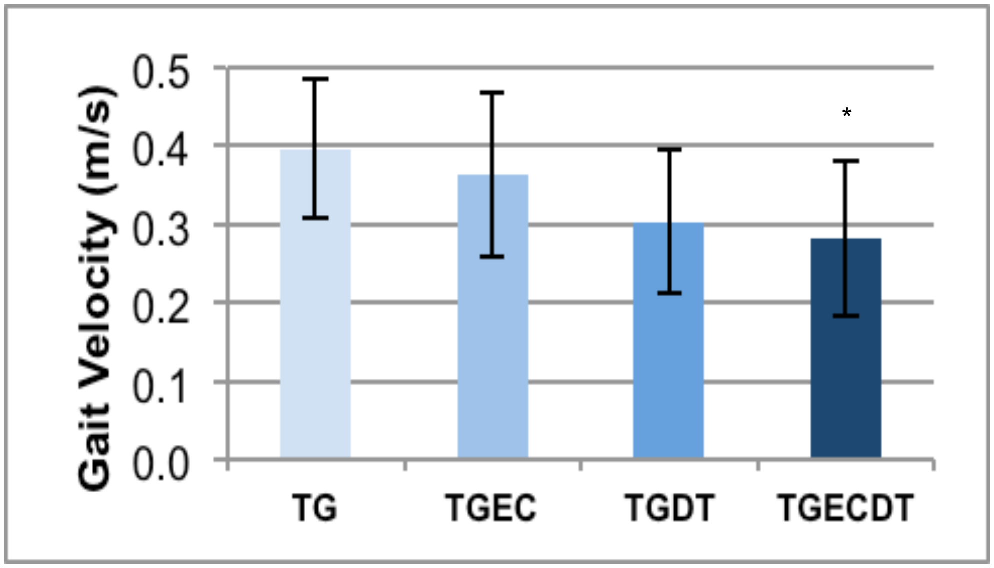

Figure 1. Effect of condition on velocity (m/s) during tandem gait.
Nine healthy college-aged subjects completed tandem gait under 4 conditions. * Indicates slower velocity as compared to TG and TGEC. TG = tandem gait; TGEC = tandem gait eyes closed; TGDT = tandem gait dual-task; TGDTEC = tandem gait dual-task with eyes closed.

CHAPTER III: METHODOLOGY

Specific Aim 1

Design and Setting

We recruited a convenience sample of 30 college-aged recreational athletes (no varsity inter-collegiate athletes were included). There were two groups (15 participants in each group): 1) Recent concussion group (median time since concussion of 126 days, range 28-432 days), and 2) Matched control group with no recent concussions. Control participants were matched to each injured participant based on sex, age (± 1 year), mass (± 10%), and height (± 5%). Participants must have reported being moderately physically active for at least 30 minutes 3 times a week. We excluded participants for any of the following conditions: attention deficit hyperactivity disorder, seizure disorders, lower extremity injury resulting in physical activity time loss of ≥3 days within the last 6 months, any history of lower extremity or low back surgery, concussion requiring admittance to the hospital, any current concussion symptoms, or a previous history of >3 concussions. For inclusion in the concussed group, participants must have sustained a concussion diagnosed by a medical professional within the last 1.5 years. Participants in the matched control group must have been without diagnosed concussion for at least 3 years. We recorded the number of days since the most recent concussion in the concussed group. The Institutional Review Board at the University of North Carolina at Chapel Hill approved our study and all participants signed an informed consent document prior to testing.

Instrumentation

The Zeno Walkway (ProtoKinetics, Havertown, PA) collects pressure data during static and dynamic balance and gait assessment. The Zeno Walkway contains a 16-level pressure sensing pad and circuitry inside a low profile and portable housing. The walkway is 16 feet long by 2 feet wide and allows for analysis in a single pass or multiple passes. ProtoKinetics Movement Analysis Software (PKMAS) allows for recording and analysis of spatiotemporal and dynamic balance variables. The technology employed by the Zeno Walkway has been shown to have strong concurrent validity and good to excellent test-retest reliability for the assessment of spatiotemporal gait variables.[98-100] Our own internal testing revealed excellent center of pressure outcome reliability ($ICC_{2,k}$ >0.963) and strong correlations to force plate center of pressure outcomes (r>0.75).

Data Collection Procedures

All data collection took place in a single session lasting approximately 2 hours. Tandem gait testing consisted of 4 conditions: 1) eyes open, 2) eyes closed, 3) eyes open with a dual-task, and 4) eyes closed with a dual-task. The 4 gait conditions were randomized within each testing session for each subject. Prior to testing, the participant was allowed to familiarize himself/herself with the 4 conditions by completing a minimum of 1 practice trial of each. Participants were instructed to complete the tandem gait task as fast as possible while maintaining their best balance throughout each trial. The participants started with both feet together at one end of the walkway and were required to touch their toes to their heel on each step. Participants completed 3 trials of each tandem gait condition, with a trial defined as one trip down the 16-foot walkway. Participants did not wear shoes during tandem gait. During dual-task conditions, the trial was stopped based on whichever of the following scenarios occurred first: 1) The participant reached the end of the walkway, or 2) The participant completed the cognitive task portion of the dual-task condition. It was necessary to end the trial after the cognitive task was completed in order to ensure all footfalls of a given trial were recorded while the participant was under dual-task conditions.

The cognitive task used during the dual-task conditions was the Brooks Visuospatial Task,[101] which has been previously used to investigate dual-task effects on gait following concussion.[18] The Brooks Visuospatial Task was chosen as our pilot data indicated significantly slower tandem gait velocities during dual-task trials using this cognitive task. Additionally, the Brooks Visuospatial Task challenges the visuospatial component of cognition. This may be important post-concussion, as an increased cognitive-motor association has been observed, suggesting damage to a shared cognitive-motor component such as visuospatial attention.[102] Each participant had one minute to memorize the order of digits 1-8 on a 4x4 grid (**Figure 2**). After the minute-long period, the participant identified the position of the next consecutive digit without looking at the grid. For example, participants presented with the grid in **Figure 2** would say, "1st row, 1st column, 1, right 2, down 3, right 4, down 5, down 6, left 7, left 8." During dual-task conditions, specific directions were given that instructed the participant to focus on maintaining fast and balanced tandem gait while trying their best to accurately complete the cognitive task. Error frequency and time taken to complete the Brooks Visuospatial Task were recorded by the primary investigator using a stopwatch during all trials involving the Brooks task. Prior to any tandem gait trials, each participant completed 3 baseline Brooks Visuospatial Tasks while seated to ensure task familiarization.

Data Reduction and Analysis

Center of pressure data were collected at 120 Hz and were filtered by the PKMAS software a using a second-order low-pass Butterworth filter with a cutoff frequency of 10 Hz. Data were first processed in PKMAS. Individual footfalls were combined and treated as a single footfall, resulting in continuous time-series center of pressure data for each trial. This was necessary as identifying individual footfalls post-data collection with the PKMAS software was not possible due to inability to separate continuous heel-toe foot contacts. A custom Matlab (Matlab v8.0, The MathWorks Inc., Natick, MA) program was created to reduce the data and calculate all outcomes listed in **Table 4**. The first 140 cm of each trial were analyzed. This was necessary because trials were stopped when the participant finished the Brooks Visuospatial Task during conditions 3 and 4. Several cut-points were explored, and the 140 cm cut-point resulted in the least amount of discarded trials (n=1) while still capturing multiple footfalls during a given trial. This distance allowed for at least 4 footfalls per trial per participant, which is more than has been analyzed and previously reported.[56, 62, 103]

Data were averaged across all trials for each condition, and these average values were used for all statistical analyses. To explore tandem gait velocity, speed, and center of pressure path, we utilized a 4 (condition) x 2 (group) mixed-model analysis of covariance (ANCOVA). Brooks Visuospatial Task time to task completion was analyzed using a 3 (condition, including Brooks Visuospatial Task baseline, dual-task eyes open, and dual-task eyes closed) x 2 (group) mixed-model ANCOVA. Bonferroni corrected t tests were used to analyze any significant interactions or main effects. Dual-task cost was analyzed utilizing a between subjects ANCOVA. Because velocity was statistically different between groups, it was used a covariate when investigating center of pressure speed and path as well as all center of pressure dual-task outcomes. Additionally, we covaried for the number of days between the last concussion and the testing session in all statistical models. The number of days post-injury for each concussion group participant was subtracted from the group mean days since concussion (177 days). Control participants were assigned a value of zero. This created a mean centered days since concussion value, which was used as a covariate in all statistical models. An a priori alpha value of 0.05 was established.

Dual-task cost was calculated separately for eyes open and eyes closed conditions. When interpreting DTC, positive values indicate worse performance during dual-task conditions. To investigate dual-task effects on cognitive performance, errors on the Brooks Visuospatial Task were converted to percent of correct responses. This outcome was combined with time to complete the Brooks Visuospatial Task to form a single combined dual-task cost outcome for the cognitive task.

Specific Aim 2

Design and Setting

The study participants and exclusion criteria for Aim 2 were identical to Aim 1.

Instrumentation

The Vicon System (Vicon Motion Systems, Centennial, CO) consists of 10 infrared video cameras in conjunction with two piezoelectric non-conductive force platforms (Model #4060-NC Bertec Co., Columbus, OH) embedded in the floor. Each participant was outfitted with 20 individual retro-reflective markers affixed to the skin or spandex over the jugular notch, the tip of each shoulder, the L5 area of the low back, bilaterally on the anterior-superior iliac spine of the pelvis, greater trochanter, medial epicondyle of the femur, lateral epicondyle of the femur, medial malleolus, lateral malleolus, first metatarsal head, and fifth metatarsal head. Cluster markers were affixed over the sacrum and bilaterally on each thigh, shank, and foot. Left side clusters consisted of 4 retro-reflective markers while the right side and sacral clusters consisted of 3 markers. Following an initial static trial, all individual markers except those at the tip of each shoulder and jugular notch were removed and the participant completed the testing with the clusters. Kinematic data were collected at 150 Hz and calibrated for a 4m long x 3m wide x 2.5m high volume while kinetic data were collected at 1500 Hz. All video data will be time synchronized with the analog force plate data. The world axis system was established as positive anteriorly in the sagittal plane, left in the frontal plane, and superior in the transverse plane.

Data Collection Procedures

Participants completed 6 functional movement tasks. The order of the tasks was randomized for each participant. Participants were required to complete at least one practice trial of each task, but were offered practice trials until they reported feeling comfortable and confident with the task. All functional tasks are described below and all outcome variables are described in **Table 5**.

Jump Landing. Participants stood atop a 30 cm box placed a horizontal distance equal to 50% of their height behind the force plates. The participants were instructed to “get set,” meaning they were to take an athletic stance upon the box and await a stimulus to signal the beginning of the trial. A visual stimulus (green light) placed approximately 3 m in front of the participant was triggered randomly within 5 seconds by the investigator, indicating the start of the trial. The participant jumped forward off the box (told to “jump out, not up”) and performed a double-leg landing with the right foot in contact with one force plate and the left foot in contact with the other force plate before jumping vertically for maximal height. The participant was instructed to initiate the movement as quickly as possible following the visual stimulus. Each participant completed 5 jump landings.

Anticipated Cut. Participants stood atop a 30 cm box placed a horizontal distance equal to 50% of their height behind the force plates. The participants were instructed to “get set,” meaning they were to take an athletic stance upon the box and await a stimulus to signal the beginning of the trial. A visual stimulus (green light) placed approximately 3 m in front of the participant was triggered randomly within 5 seconds by the investigator, indicating the start of the trial. The participant jumped forward off the box (told to “jump out, not up”) and landed on a single leg. Immediately upon landing, the participant cut at a 45° angle in the direction provided by the investigator prior to the trial (cut towards dominant = land on non-dominant foot, cut towards non-dominant = land on dominant foot). Each participant completed 5 trials cutting in each direction (10 total trials).

Unanticipated Cut. Participants stood atop a 30 cm box placed a horizontal distance equal to 50% of their height behind the force plates. The participants were instructed to “get set,” meaning they were to take an athletic stance upon the box and await a stimulus to signal the beginning of the trial. A visual stimulus (green light) placed approximately 3 m in front of the participant was triggered randomly within 5 seconds by the investigator, indicating the start of the trial. The participant jumped forward off the box (told to “jump out, not up”) and landed on a single leg. Immediately upon landing, the participant cut at a 45° angle. For the unanticipated cut, the participant was not informed which direction to cut. As the participant jumped from the box, they triggered a timing gate set at 0.76 m behind the force plates. This distance was chosen to maximize the time each participant would have to react to the directional stimulus, but be in a position where shorter participants would not be excluded. This timing gate triggered a visual stimulus (set of blue and green lights) to the participants left or right. Participants were instructed to cut towards the light in the same manner as the anticipated cutting task above (cut towards dominant = land on non-dominant foot, cut towards non-dominant = land on dominant foot). Each participant completed 10 total trials, regardless of whether or not they were performed correctly. Trials were discarded if the participant did not land appropriately on a single leg or cut in the wrong direction.

Single Leg Squat. Participants were asked to stand on a single leg, with their toes facing forward. The non-weight bearing leg was flexed to 90° at the knee approximately 75° at the hip, the hands placed on the hips, and the head and eyes facing forward. Participants flexed their weight-bearing knee to a squat, to maximal comfort, and then returned to the upright posture. Participants performed 5 single leg squat trials on each leg. Each trial consisted of 5 squat repetitions completed without pause at a self-selected pace.

Single Leg Hop. Participants stood atop a 30 cm box placed a horizontal distance equal to 50% of their height behind a force plate. Participants placed both hands on their hips and jumped off the box with both feet and landed on a single leg. Participants were instructed to come to a stable position as quickly as possible upon landing. The total trial time was 10 seconds, with participant holding their best single leg posture for as much of the trial as possible. Participants performed 5 single leg hop trials on each leg (10 total trials).

Proprioception. Participants stood with feet approximately shoulder width apart and closed their eyes. Initially, the participant squatted to 60° of knee flexion while the investigator used a goniometer to confirm the appropriate knee flexion angle over the right knee. A tripod was then placed so that it touched the upper right thigh of the participant while they were in 60° of knee flexion. Next, a single 8-second trial was completed with the tripod in place. Following this reference trial, the tripod was removed and the participant was instructed to squat to a knee flexion angle that replicated the knee flexion angle of the initial trial. The participant depressed a handheld trigger synced to our data collection system when they believed they had replicated the initial trial knee flexion angle and held the squat until trial completion. A total of 6 trials were performed, 1 reference trial with the tripod in place and 5 test trials with no tripod. This method was a variation of previously reported closed kinetic chain joint position sense measurements.[104, 105]

Data Reduction and Analysis

All kinematic and kinetic data were imported into Motion Monitor v8.0 (Innovative Sports Training Inc., Chicago, IL) to calculate Euler joint angles. Joint motion was defined as the distal segment moving relative to the proximal segment, except trunk motion in the frontal and sagittal planes, which was defined as trunk segment movement relative to the world axis. Positive in the sagittal plane indicates flexion at the trunk and knee, and extension at the hip. Positive in the frontal plane indicates adduction at the hip, varus angle at the knee, and right lateral trunk flexion. All kinematic data were filtered with a fourth-order low-pass Butterworth filter with a cutoff frequency of 10 Hz. For single leg squat center of pressure outcomes, kinetic data were filtered with a fourth-order low-pass Butterworth filter with a cutoff frequency of 14 Hz. For single leg hop outcomes, kinetic data were filtered with a second-order low-pass Butterworth filter with a cutoff frequency of 12.53 Hz.[106] Data were then exported to custom Matlab software to identify all dependent variables of interest. Dependent variables are defined in **Table 5**.

Position of the bottom sacral cluster marker in the sagittal and transverse planes was analyzed for 0.5 seconds prior to onset of the visual stimulus. The mean position of the marker was calculated in each plane. First movement during jump landing, anticipated cutting, and unanticipated cutting was defined as the first movement of the bottom sacral cluster marker in either the sagittal or transverse plane exceeding 3 cm from the mean marker position prior to the visual stimulus onset. Reaction time was defined as the time in seconds from visual stimulus onset to first movement. Reaction time cost (RTC) has not been previously validated in the literature. As noted in the formula presented in **Table 5**, reaction time cost is modeled after the previously validated dual-task cost formula. This formula allows for comparison between participants and groups as it standardizes participant scores by baseline performance. In the case of RTC, baseline performance will be the reaction time recorded for the simplest task, the jump landing. We initially compared reaction time during anticipated cuts to the dominant and non-dominant sides utilizing a paired samples t test. No between cut direction differences were observed (t_{27}=0.84; p=0.410), so we combined reaction time outcomes for cuts to the dominant and non-dominant side. Because 5 jump landing trials were performed, we used the first 5 successfully completed anticipated and unanticipated cuts (out of 10 total trials) when analyzing reaction time and RTC.

Trunk, hip, and knee joint angles at initial ground contact were calculated in the sagittal and frontal planes during jump landing and both cutting tasks. Initial ground contact was defined as greater than or equal to 10 N as measured by the force plate. Dependent variables for jump landing are reported as angles of the dominant limb. Joint angles during cuts toward the dominant and non-dominant sides were analyzed separately.

Time to stabilization was calculated during the single hop task. Time to stabilization methodology has been previously described in detail.[58] Specifically, resultant ground reaction force was calculated by squaring each time series value of the anterior/posterior and medial/lateral ground reaction forces during the last second of each trial.[107] These values were summed and the square root was taken to arrive at a single resultant ground reaction force value, which was normalized to bodyweight.[108] This was done for each control participant, and the group mean and standard deviation were calculated to determine the resultant ground reaction force range of variation. Three standard deviations were added to the mean range of variation, and this value was multiplied by each participant's bodyweight to get a normalized reference value for each participant. The resultant ground reaction force was fit with an unbounded third-order polynomial, and time to stabilization was defined as the time when the curve fell below the normalized reference value. Because a paired samples t test comparing time to stabilization for dominant and non-dominant limbs was nearly significant (mean difference=0.21 s; t_{29}=2.00; p=0.055), we compared group time to stabilization values individually by dominant and non-dominant limbs.

For the proprioception task, the absolute difference of the knee flexion angle between the reference trial and each of the 5 test trials was calculated analyzed.

No statistical differences were observed when comparing dominant to non-dominant limb during the single leg squat task ($p \geq 0.102$). Thus, we combined data from each limb to create a single group mean for each dependent variable.

To explore reaction time outcomes, we utilized a 3 (condition) x 2 (group) mixed-model ANCOVA. We utilized a between subjects ANCOVA for all other outcomes. We covaried for the number of days between the last concussion and the testing session in all statistical models as described above in the methodology for Specific Aim 1. An a priori alpha value of 0.05 was established.

Reaction-time cost was calculated separately for anticipated cut and unanticipated cut conditions. In both cases, reaction time values were compared back to jump landing reaction time values. When interpreting RTC, positive values indicate increased reaction time during cut trials as compared to jump landing trials.

1	2		
	3	4	
9		5	
8	7	6	

Figure 2. Example of a Brooks Visuospatial Task card.

Table 4. Tandem gait outcome variables.

Variable	Definition
Velocity	Center of pressure range of motion in the sagittal plane divided by trial time (cm/s)
COP Path Length	Total center of pressure path length trial start to end (cm)
COP Speed	Center of pressure path length divided by trial time (cm/s)
Dual-Task Cost[a]	(Dual task variable – Single task variable / Single task variable) x 100 (%)
Brooks Visuospatial Task Time	Time taken to complete the Brooks Visuospatial Task, including baseline trials (s)
Brooks Visuospatial Task Errors	Number of correct responses on a given trial of the Brooks Visuospatial Task divided by total number of responses (%)

[a] Dual-Task Cost calculated separately for eyes open and closed conditions. Positive dual-task cost values represent worse performance during dual-task conditions. COP = Center of pressure

Table 5. Outcome variables associated with Aim 2.

Task	Variable	Definition
Jump Landing **Anticipated Cutting** **Unanticipated Cutting**	Reaction Time (RT)	Difference in time (s) between visual stimulus and total displacement of 3 cm along the sagittal or transverse axis of the bottom sacral cluster marker
	Knee Angles	Knee sagittal and frontal plane angles measured at point of initial ground contact (degrees)
	Hip Angles	Hip sagittal and frontal plane angles measured at point of initial ground contact (degrees)
	Trunk Angles	Trunk sagittal and frontal plane angles measured at point of initial ground contact (degrees)
Anticipated Cutting **Unanticipated Cutting**	Reaction Time Cost	(Anticipated RT or Unanticipated Cut RT - Jump Landing RT / Jump Landing RT) x 100 (percent)
Single Leg Squat	Center of Pressure Path	Total path of the center of pressure (cm)
	Center of Pressure Speed	Total path of the center of pressure divided by trial time (cm/s)
	Center of Pressure Velocity	Center of pressure displacement divided by time in both the sagittal and frontal planes (cm/s)
	Sacrum Displacement	Maximum range of motion of the bottom sacral cluster marker in the transverse plane (cm)
	Sacrum Speed	Maximum range of motion of the bottom sacral cluster marker in the transverse plane divided by trial time (cm/s)
Single Leg Hop	Time to Stabilization	Time until resultant ground reaction force fell below mean range of variation plus 3 standard deviations[107]
Proprioception	Absolute Knee Flexion Angle Difference	Mean knee flexion angle during squat. The absolute difference between the reference trial (trial 1) and test trials 2-6 (degrees)

CHAPTER IV: MANUSCRIPT 1

FUNCTIONAL BALANCE ASSESSMENT IN RECREATIONAL COLLEGE-AGED INDIVIDUALS WHO RECENTLY EXPERIENCED A CONCUSSION

Introduction

Concussion is a complex pathophysiologic process that can affect many areas of cognition and motor control.[32, 45, 109] Clinicians often rely on athlete self-report of concussion symptoms, as outward signs of the injury may not be present. Athletes may fail to report concussion symptoms, leading to a high rate of undiagnosed brain injury in sport settings.[3] Several concussion evaluation tools have been developed and validated, including graded symptom checklists[4] and objective measures of neurocognition[6] and static balance.[7] Using these clinically based tools as markers of recovery, over 85% of concussed individuals recover within 7 days.[8]

But are concussed individuals truly ‘recovered’ when they perform at baseline levels on these measures? Those who have suffered a concussion are 3 to 6 times more likely to suffer a subsequent concussion.[9, 10] More in-depth tools such as transcranial magnetic stimulation[21, 22] and electroencephalography[110] have revealed functional brain abnormalities remaining after traditional recovery. Further, a growing body of literature suggests athletes are at increased risk for suffering musculoskeletal injuries following concussion.[11-14] Taken together, these studies suggest there may be lingering functional impairments following recovery on traditional measures of neurocognition and static balance.

Dynamic balance is affected during gait following concussion.[15, 62] Multiple investigators report dynamic balance measures during gait may be sensitive to brain injury even after recovery on traditional measures,[57, 62] with one study detailing gait deficits in a cohort that was assessed over 6 years after sustaining concussion.[18] Dynamic balance deficits during gait appear to be more pronounced when individuals perform in dual-task environments.[15, 16, 62] Dual-task protocols consist of completing a motor task, in this case gait, while concurrently performing a cognitive task. Although the cognitive task varies, some common examples include counting backwards by sevens, reciting the months of the year backwards, or completing a visual-spatial memory task. These results have all been observed during standard gait, and no clinically feasible dynamic balance assessments have been proposed. Thus, understanding dynamic balance during a more challenging motor task that has the potential to illicit objectively identifiable balance errors may begin to inform an appropriate dynamic balance clinical assessment.

Tandem gait has been suggested as a valid, cost-effective, and clinician friendly means of objectively identifying post-concussion deficits.[19] Unfortunately, the tandem gait task included in the Sport Concussion Assessment Tool-3rd Edition (SCAT3)[19] was created without any scientific validity or evidence of how concussion affects tandem gait. In the current version, tandem gait pass or fail is based on a single measure of time to task completion. Based on this single criterion, 80% of healthy high school athletes fail the tandem gait task.[20] While the current tandem gait task may be a useful tool in the effort to assess dynamic balance, it currently lacks the appropriate specificity to function as a clinical tool. Understanding how dynamic balance during tandem gait is affected by concussion is an important step in developing a clinical tool to appropriately assess for important post-concussion deficits not currently evaluated. Increasing neuromechanical constraints by adding a cognitive distractor task during tandem gait may further challenge the ability of the patient to maintain neuromuscular control.

Thus, the purpose of this investigation was to identify in a preliminary manner whether there are tandem gait dynamic balance differences in recently (within the last 1.5

years) concussed, relative to non-concussed recreational athletes. Our underlying hypothesis of interest is that a history of sport-related concussion may result in dynamic balance deficits during tandem gait that are still identifiable after the athlete has returned to play due to lingering motor control deficits from the injury that are unaccounted for by conventional concussion assessment tools. This preliminary study was seen as an initial investigation designed to facilitate the design of a larger study.

Methods

Design and Setting

We recruited a convenience sample of 30 college-aged recreational athletes (no varsity inter-collegiate athletes were included). There were two groups (15 participants in each group): 1) Recent concussion group (median time since concussion of 126 days, range 28-432 days), and 2) Matched control group with no recent concussions. Control participants were matched to each injured participant based on sex, age (± 1 year), mass (± 10%), and height (± 5%). For inclusion in the concussed group, participants must have sustained a concussion diagnosed by a medical professional within the last 1.5 years. Participants in the matched control group must have been without diagnosed concussion for at least 3 years. Participants were excluded for any of the following: attention deficit hyperactivity disorder, seizure disorders, lower extremity injury resulting in physical activity time loss of ≥3 days within the last 6 months, any history of lower extremity or low back surgery, concussion requiring admittance to the hospital, any current concussion symptoms, or a previous history of >3 concussions. Additionally, we recorded the number of days since the most recent concussion in the concussed group. The Institutional Review Board at the University of North Carolina at Chapel Hill approved our study and all participants signed an informed consent document prior to testing.

Instrumentation

The Zeno Walkway (ProtoKinetics, Havertown, PA) was used to collect center of pressure data during tandem gait assessment. The Zeno Walkway contains a 16-level pressure sensing pad and circuitry inside a low profile and portable housing. The walkway is 16 feet long by 2 feet wide and allows for analysis in a single pass or multiple passes. ProtoKinetics Movement Analysis Software (PKMAS) allows for recording and analysis of spatiotemporal and dynamic balance variables. The technology employed by the Zeno Walkway has been shown to have strong concurrent validity and good to excellent test-retest reliability for the assessment of spatiotemporal gait variables.[98-100] Our own internal testing revealed excellent center of pressure outcome reliability ($ICC_{2,k}$>0.963) and strong correlations to force plate center of pressure outcomes (r>0.75).

Data Collection Procedures

All data collection took place in a single session. Tandem gait testing consisted of 4 conditions: 1) eyes open, 2) eyes closed, 3) eyes open with a dual-task, and 4) eyes closed with a dual-task. The 4 gait conditions were randomized within each testing session for each subject. Prior to testing, the participant was allowed to familiarize himself/herself with the 4 conditions by completing a minimum of 1 practice trial of each. Participants were instructed to complete the tandem gait task as fast as possible while maintaining their best balance throughout each trial. The participants started with both feet together at one end of the walkway and were required to touch their toes to their heel on each step. Participants completed 3 trials of each tandem gait condition, with a trial defined as one trip down the 16-foot walkway. During dual-task conditions, the trial was stopped based on whichever of the following scenarios occurred first: 1) The participant reached the end of the walkway, or 2) The participant completed the cognitive task portion of the dual-task condition. It was necessary to end the trial after the cognitive task was completed in order to ensure all footfalls of a given trial were recorded while the participant was under dual-task conditions.

The cognitive task used during the dual-task conditions was the Brooks Visuospatial Task,[101] which has been previously used to investigate dual-task effects on gait following concussion.[18] Each participant had one minute to memorize the order of digits 1-8 on a 4x4 grid (**Figure 2**). After the minute-long period, the participant identified the position of the next consecutive digit without looking at the grid. For example, participants presented with the grid in **Figure 2** would say, "1st row, 1st column, 1, right 2, down 3, right 4, down 5, down 6, left 7, left 8." During dual-task conditions, specific directions were given that instructed the participant to focus on maintaining fast and balanced tandem gait while trying their best to accurately complete the cognitive task. Error frequency and time taken to complete the Brooks Visuospatial Task were recorded during all dual-task trials. Prior to any tandem gait trials, each participant completed 3 baseline Brooks Visuospatial Tasks while seated.

Data Reduction and Analysis

This was necessary as identifying individual footfalls post-data collection with the PKMAS software was not possible. A custom Matlab (Matlab v8.0, The MathWorks Inc., Natick, MA) program was created to reduce the data and calculate all outcomes listed in **Table 4**. The first 140 cm of each trial were analyzed. This was necessary because trials were stopped when the participant finished the Brooks Visuospatial Task during conditions 3 and 4. Several cut-points were explored, and the 140 cm cut-point resulted in the least amount of discarded trials (n=1) while still capturing multiple footfalls during a given trial. This distance allowed for at least 4 footfalls per trial per participant, which is more than has been analyzed and previously reported.[56, 62, 103]

Data were averaged across all trials for each condition, and these average values were used for all statistical analyses. To explore tandem gait velocity, speed, and center of pressure path, we utilized a 4 (condition) x 2 (group) mixed-model analysis of covariance (ANCOVA). Brooks Visuospatial Task time to task completion was analyzed using a 3 (condition, including Brooks Visuospatial Task baseline, dual-task eyes open, and dual-task eyes closed) x 2 (group) mixed-model ANCOVA. Bonferroni corrected t tests were used to analyze any significant interactions or main effects. Dual-task cost was analyzed utilizing a between subjects ANCOVA. Because velocity was statistically different between groups, it was used as a covariate when investigating center of pressure speed and path as well as all center of pressure dual-task outcomes. Additionally, we covaried for the number of days between the last concussion and the testing session in the injured group. The number of days post-injury for each concussion group participant was subtracted from the group mean days since concussion (177 days). Control participants were assigned a value of zero. This created a mean centered days since concussion value, which was used as a covariate in all statistical models. An a priori alpha value of 0.05 was established.

Dual-task cost was calculated separately for eyes open and eyes closed conditions. When interpreting DTC, positive values indicate worse performance during dual-task conditions. To investigate dual-task effects on cognitive performance, errors on the Brooks Visuospatial Task were converted to percent of correct responses. This outcome was combined with time to complete the Brooks Visuospatial Task to form a single combined dual-task cost outcome for the cognitive task.

Results

Independent t tests comparing demographics revealed no statistically significant group differences. Median days since concussion in the concussed group was 126 days (range 28-432 days). One participant in the control group reported a history of 2 concussions, the most recent of which was 1,103 days prior to testing. No other control participants reported a history of concussion. Full group demographics and between group comparisons are presented in **Table 6**.

Dynamic Balance. No significant group by condition interactions were observed for tandem gait center of pressure path ($F_{3,83}$=1.10; p=0.353), velocity ($F_{3,83}$=0.45; p=0.715), or speed ($F_{3,83}$=0.32; p=0.810). We observed a significant group main effect for tandem gait velocity ($F_{1,27}$=4.26; p=0.049; ES=0.38), with the concussion group (25.2 cm/s, 95% CI: 22.3-28.0) walking significantly slower than the control group (29.2 cm/s, 95% CI: 26.4-

32.0). No other group main effects were observed. **Table 7** details dynamic balance outcomes during tandem gait.

Significant main effects for condition were observed for tandem gait center of pressure path ($F_{3,83}$=13.21; p<0.001), velocity ($F_{3,83}$=147.67; p<0.001), and speed ($F_{3,83}$=29.65; p<0.001). Participants displayed significantly greater center of pressure path during tandem gait with eyes closed and Brooks Visuospatial Task (197.3 cm) as compared to tandem gait (177.2 cm; p=0.009) and tandem gait with Brooks Visuospatial Task (168.0 cm: p<0.001). Additionally, greater center of pressure path was noted during tandem gait with eyes closed (188.8 cm) as compared to tandem gait with Brooks Visuospatial Task (p=0.001). Participants displayed significantly greater center of pressure speed during tandem gait with eyes closed (35.7 cm/s) as compared to both tandem gait (33.2 cm/s; p<0.001) and tandem gait with Brooks Visuospatial Task (32.1 cm/s; p<0.001). Greater center of pressure speed was also noted during tandem gait with eyes closed and Brooks Visuospatial Task (35.1 cm/s) as compared to tandem gait with Brooks Visuospatial Task (p<0.001). Velocity was greater during tandem gait (34.4 cm/s) as compared to all other conditions (p<0.001), while slower velocity was noted during tandem gait with eyes closed and Brooks Visuospatial Task (21.3 cm/s) as compared to all other conditions (p<0.001). Velocity was also greater during tandem gait with Brooks Visuospatial Task (24.1 cm/s) as compared to tandem gait with eyes closed (28.9 cm/s; p<0.001). **Table 7** details dynamic balance outcomes during tandem gait.

Dual-Task Cost. A significantly greater dual-task cost was observed for center of pressure speed during eyes closed trials ($F_{3,26}$=5.13; p=0.032) such that the concussion group (23.5%) reduced their center of pressure speed to a greater extent than did the control group (16.3%) during the eyes closed dual-task condition. No other center of pressure dual-task cost outcomes were significant (p>0.068). Center of pressure dual-task cost comparisons are presented in **Figures 3** and **4**.

Brooks Visuospatial Task. There were no errors in the majority of Brooks Visuospatial Task trials. Thus, we did not analyze Brooks Visuospatial Task errors independently, but did include errors with time to complete the task in the Brooks Visuospatial Task as a combined measure for the dual-task cost (%) variable. No significant group by condition interactions were noted for Brooks Visuospatial Task time ($F_{2,56}$=1.36; p=0.266). There were no main effects for group ($F_{1,27}$=4.07; p=0.054; ES=0.37), but we did observe a significant main effect for condition ($F_{2,56}$=17.22; p<0.001) such that tandem gait with eyes open and Brooks Visuospatial Task (12.4 s; t_{56}=4.69; p<0.001) and tandem gait with eyes closed and Brooks Visuospatial Task (12.7 s; t_{56}=5.40; p<0.001) trials took longer to complete than baseline Brooks Visuospatial Task trials (10.4 s).

No group differences were observed for Brooks Visuospatial Task combined dual-task cost during eyes open ($F_{3,27}$=1.11; p=0.301; concussion group=32.4%, 95% CI:15.5-49.3; control group=20.1%, 95% CI: 3.2-37.0) or eyes closed conditions ($F_{2,27}$=1.98; p=0.170; concussion group=37.5%, 95% CI: 21.9-53.1; control group=22.4%, 95% CI :6.8-38.0).

Discussion

We are the first to study tandem gait outcomes after concussion, even though international concussion experts have recommended a tandem gait assessment following concussion.[19] Our intention was to provide preliminary analysis of novel outcomes, hopefully leading to more in-depth study of these potentially important clinical outcomes. We failed to reject the null hypotheses for most variables, but we did observe slower tandem gait velocity in those with a recent concussion history as compared to healthy controls. We also observed greater dual-task cost on center of pressure speed in recently concussed individuals as compared to healthy controls. Our findings must be regarded as extremely tentative. We lack pre-injury data on our participants. Thus, we cannot eliminate the possibility that these two groups may have differed on tandem gait conditions prior to the onset of injury. Additionally, our limited sample size of 15 per group means that these findings must be treated as tentative.

Previous investigations of standard gait outcomes following concussion have investigated cohorts acutely until approximately 30 days after the injury. Utilizing the same cognitive task applied here, Martini et al.[18] reported significantly slower gait velocity in a cohort of previously concussed individuals who were over 6 years post-concussion on average. Because our study was the first to investigate tandem gait after recovery from concussion, making comparisons to previous literature that investigated standard gait outcomes is difficult. Proportional mean difference, obtained by dividing the observed group difference by the overall mean velocity and then multiplying by 100, may provide some insight when comparing our findings to previous literature. Using this standardization, we observed a 15% proportional mean difference between groups in tandem gait velocity. Previous reports of standard gait following concussion report statistically significant velocity mean differences between previously concussed and control participants, but proportionately the differences are around 7 or 8%.[18, 27] While gait deficits up to 30 days post-injury are well established, it is unclear how long these deficits may persist. Our proportional difference was about twice those referenced above, but the clinical meaningfulness of this finding is unclear. Our participants were asymptomatic and had no physical or cognitive activity limitations. Thus, our observed difference, while proportionally greater than previous findings, may not reflect any deficit in normal physical functioning.

We found increased time to complete the Brooks Visuospatial Task while walking, suggesting slower cognitive performance during walking compared to sitting (in both groups). Further discussion of motor and cognitive performance under dual-task conditions is warranted. Plummer et al.[54] describes several potential cognitive motor interference outcomes during dual-task. While many combinations are possible (i.e. improved cognitive performance with no change in motor performance, worse cognitive performance with improved motor performance, etc.), our results suggest a mutual interference during dual-task tandem gait. Mutual interference refers to a worsening cognitive performance accompanied by a worsening motor performance. Along with this increased Brooks Visuospatial Task time, we report increased center of pressure path during dual-task conditions and decreased center of pressure speed, suggesting a decline in balance performance. It is important to note these differences were observed across groups; they were not specific to just concussed participants. Our data are evidence for mutual interference of our cognitive and motor task combination in both previously concussed and non-concussed matched individuals. Both groups appear to demonstrate a greater cognitive cost relative to motor cost. When comparing groups, the previously concussed individuals demonstrate a greater cost, especially for our combined cognitive outcome variable. Although our data show trends towards worse performance in the concussed group, we lacked statistical significance in most cases. Although we cannot say with certainty from our data, it is possible this same mutual interference is occurring in dynamic athletic settings. If so, athletic performance might be decreased and musculoskeletal injury risk increased. Further study should include sport performance and injury risk outcomes, allowing for further clinical interpretation as to the effects of mutual interference in the sport setting.

For most comparisons, we failed to reject the null hypotheses that there were no group differences. There may be several reasons why we did not observe significant differences. First, we examined a fairly small sample of injured participants. We had sufficient power to observe between group differences; however, we may have lacked the power necessary to draw definitive conclusions from our mixed-model analyses. This is certainly an important limitation to consider when interpreting our results. We report effect sizes and confidence intervals in an effort to present the reader with as much information about our preliminary findings as possible.

Another potential reason we did not observe significant group differences is the wide between-subject variability in task performance, especially during dual-task conditions. Similar to a previous investigation that utilized the Brooks Visuospatial Task,[18] we found no between group cognitive performance differences. The wide-ranging performance on the Brooks Visuospatial Task may have limited our ability to detect significant cognitive performance differences between groups, if they exist. The Brooks Visuospatial Task appears effective in distracting from the motor task, based on our observed motor dual-task effects. However, due to the large amount of between-subject variability during the Brooks Visuospatial Task, it may not useful in regards to detecting true cognitive group differences. Additionally, we cannot say if other cognitive deficits remain besides those associated with visuospatial memory, as they were not assessed in this study.

Another possible explanation for our lack of significant differences may be that there are in fact no differences in tandem gait outcomes between our concussed and healthy individuals. It is possible that if there were group differences in dynamic balance acutely after the concussion, they had recovered before we investigated these outcomes, since our concussed group had a median post-injury duration of 126 days. We were limited by a cross-sectional study design. Longitudinal assessment of related outcomes is necessary to develop a further understanding of dynamic balance after brain injury.

A current shortfall in the clinical management of concussion is the lack of a clinical test to identify dynamic balance deficits or conservative adaptations following concussion that may be contributing to the relative high re-injury rate among athletes who have returned to play after concussion. The absence of a sensitive and specific clinical test to identify functional limitations in dynamic balance is surprising, considering that post-concussion gait deficits have been recognized for over a decade.[15] Standard gait is a relatively simple everyday task. Differences between healthy and concussed individuals in standard gait, while apparent using sophisticated laboratory equipment, are minimal. It is likely that clinicians will not be able to objectively observe such slight center of mass perturbations. Increasing the neuromechanical constraints of gait, such as tandem gait, that is not motor program based may exaggerate dynamic balance deficits, leading to easier observation by clinicians. More in-depth, longitudinal studies should follow this seeking to establish common components of tandem gait that are affected by concussion, both acutely and throughout the recovery process. Unfortunately, our present findings are not definitive, but subtle between-group differences observed in our data suggest that further investigation of tandem gait more acutely after concussion may be worthwhile to explore whether tandem gait could be valuable for detecting dynamic balance deficits that may be present earlier in the concussion recovery trajectory.

Several important limitations have already been discussed. Additionally, we did not examine any frontal plane outcomes, which may give insight into dynamic balance control following concussion. We were limited by the processing ability of our data collection instrumentation, but future research should develop methodology that allows for dynamic balance assessment in specific planes. We only assessed 140 cm of tandem gait data, which drastically limited the duration and number of steps available for analysis. In the future, incorporating continuous cognitive tasks, such as counting backwards by sevens, may be important to study balance during tandem gait over longer durations and distances. Despite this limitation, we feel our methodology was appropriate as many previously published standard gait investigations have been limited to analysis of a single gait cycle per trial,[57, 63, 99] less than the 4 steps we observed here.

Conclusion

We observed significantly slower gait velocities in the recently concussed group as compared to the control group, suggesting a conservative tandem gait adaptation. Due to several limitations discussed above, our findings should be interpreted cautiously. While our findings have limited clinical applicability, these preliminary data are intended to encourage future work aimed at longitudinally assessing dynamic balance following concussion. This was the first investigation utilizing tandem gait as an outcome measure following concussion. Our methodology may be more appropriate in the acute setting, especially in research paradigms that utilize baseline testing of athletes prior to concussion.

Table 6. Group demographics and statistical comparisons.

	Concussion (n = 15)	**Control** (n = 15)	**P-Value**
Age (yrs)	19.7 (0.9)	19.7 (1.6)	0.89
Height (cm)	169.2 (9.4)	172.3 (10.8)	0.41
Mass (kg)	66.0 (12.8)	71.0 (10.4)	0.25
Female (n)	9 (60.0%)	9 (60.0%)	--
Male (n)	6 (40.0%)	6 (40.0%)	--
Days Since Concussion[a]	126 (28-432)	-- [b]	--
Total Concussions[a]	1 (1-3)	0 (0-2) [b]	--

All variables are represented by the mean (SD) unless otherwise noted. [a] Reported as median (range). [b] One control participant had experienced 2 concussions, their most recent concussion was 1,103 days prior to testing. No other control participants had a history of concussion. Healthy controls were matched to each injured participant based on sex, age (± 1 year), mass (± 10%), and height (± 5%).

Table 7. Tandem gait outcomes between groups for each condition adjusted for average days since concussion and velocity in the sagittal plane.

Condition	Center of Pressure Outcome Variables					
	Path (cm)		**Speed (cm/s)**		**Velocity (cm/s)**	
	Mean (95% CI)	ES[a]	Mean (95% CI)	ES[a]	Mean (95% CI)	ES[a]
Tandem Gait (TG)						
Concussion	176.7 (164.6, 188.8)	0.02	33.5 (32.0, 34.9)	0.09	32.5 (29.5, 35.5)	0.33
Control	177.7 (163.9, 191.4)		33.0 (31.3, 34.6)		36.4 (33.4, 39.3)	
TG w/ Eyes Closed (EC)						
Concussion	193.2 (182.0, 204.4)	0.20	36.1 (34.8, 37.5)	0.16	27.3 (24.3, 30.3)	0.28
Control	184.4 (172.9, 196.0)		35.3 (33.9, 36.7)		30.5 (27.5, 33.5)	
TG w/ Brooks						
Concussion	172.0 (159.9, 184.1)	0.18	32.5 (31.1, 34.0)	0.14	21.9 (18.9, 24.9)	0.37
Control	164.1 (152.9, 175.3)		31.7 (30.4, 36.4)		26.3 (23.3, 29.3)	
TG w/ EC and Brooks						
Concussion	205.6 (192.3, 218.9)	0.37	35.1 (33.5, 36.7)	0.02	18.9 (15.9, 21.9)	0.41
Control	189.0 (177.4, 200.6)		35.0 (33.6, 36.4)		23.6 (20.6, 26.6)	

[a] Effect size was calculated as Cohen's *d*. CI = confidence interval, ES = effect size, TG = tandem gait, EC = eyes closed, Brooks = Brooks Visuospatial Task.

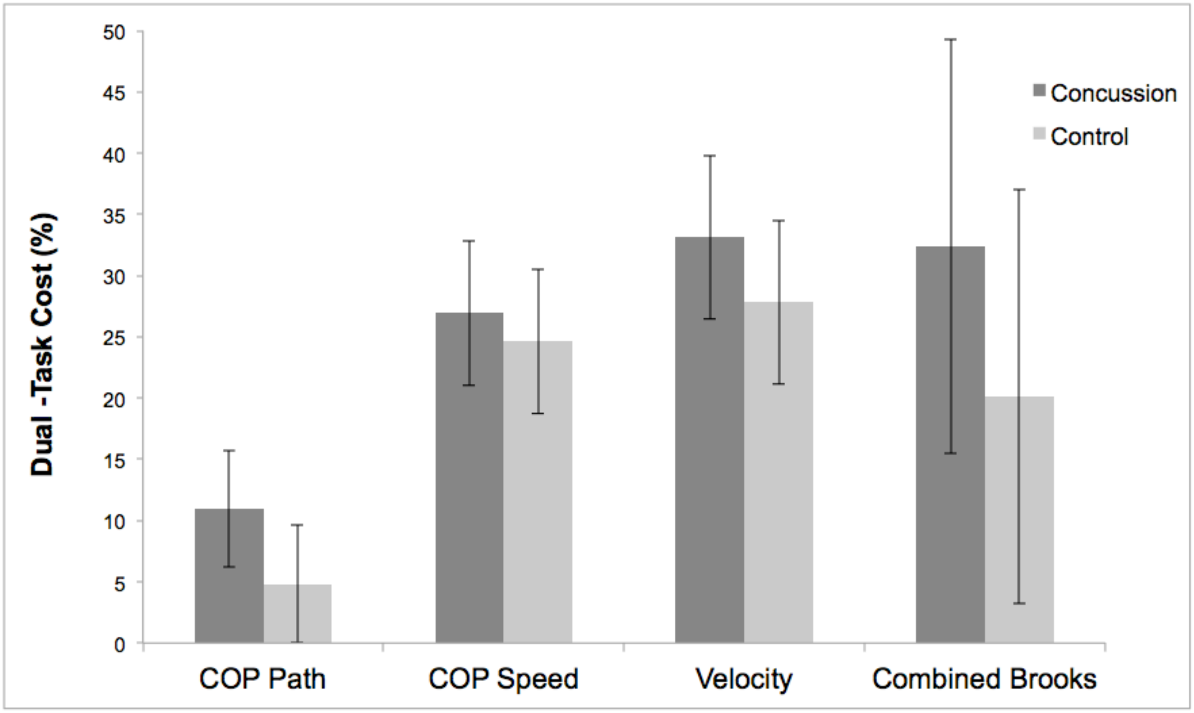

Figure 3. Dual-task cost during eyes open tandem gait conditions.
None of the between group differences were statistically significant. Error bars represent the 95% confidence intervals. COP = center of pressure; Combined Brooks = Percent correct answers and time to complete the Brooks Visuospatial Task combined.

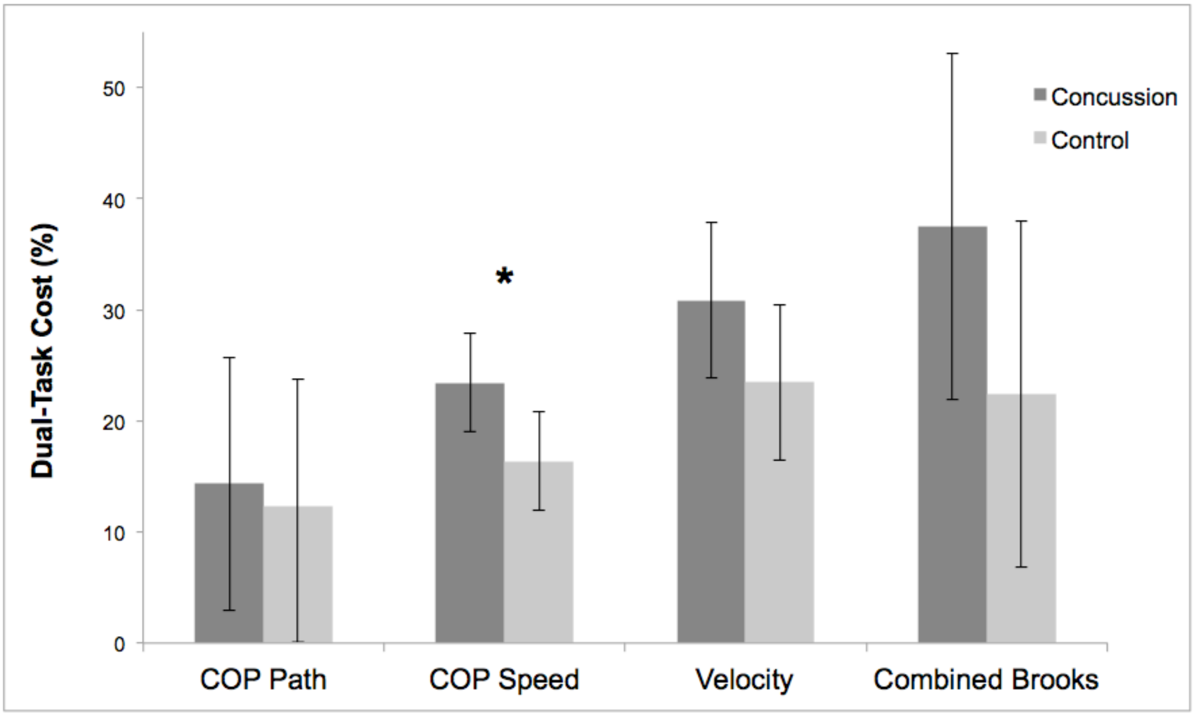

Figure 4. Dual-task cost during eyes closed tandem gait conditions.
* Indicates significant group difference ($F_{3,26}$=5.13; p=0.032). Error bars represent the 95% confidence intervals. COP = center of pressure; Combined Brooks = Percent correct answers and time to complete the Brooks Visuospatial Task combined.

CHAPTER V: MANUSCRIPT 2

FUNCTIONAL MOVEMENT AND REACTION TIME IN RECREATIONAL COLLEGE-AGE INDIVIDUALS WHO RECENTLY EXPERIENCED A CONCUSSION

Introduction

Concussion results in numerous symptom,[4] cognitive,[5, 6] and static balance deficits.[7] Common assessment measures in these domains typically demonstrate recovery in 7-10 days for the majority of athletes.[8] Researchers using more sophisticated laboratory measures have observed dynamic balance deficits during gait lasting beyond deficits observed using traditional assessment tools.[17, 50, 61] Despite these reported dynamic balance deficits, athletes continue to return to participation when they have been cleared based on traditional measures. The negative consequences of impaired dynamic balance during sport activity are unclear.

Recent reports have suggested athletes are at increased risk of musculoskeletal injury following concussion.[12-14, 26] The mechanisms underlying the increased risk of injury have not been established, but researchers have hypothesized neuromuscular control may continue to be affected following return to activity after concussion.[14, 97] Several preliminary investigations into cortical hypoexcitability after concussion have observed lower intracortical facilitation,[21] lower maximal voluntary muscle activation,[21] and increased intracortical inhibition[111] as compared to control participants. The statistically significant differences are relatively small in magnitude; however, the consequences of these mild deficits during dynamic activities of sport participation are unclear. Understanding how athletes react and move in environments that more closely resemble the dynamic nature of sport may further inform the impaired neuromuscular control hypothesis following recovery from brain injury.

The purpose of this investigation was to quantify reaction time between recently concussed and healthy control individuals during 3 functional movement tasks designed to simulate common movements on an athletic field: 1) jump landing, 2) anticipated cut, and 3) unanticipated cut. Additionally, we investigated trunk, hip, and knee joint angles at initial ground contact between recently concussed and healthy control individuals during the same 3 tasks. Our rationale was that a better understanding of reaction time and movement differences during functional movement tasks between recently concussed and healthy control individuals may inform the design of future studies of neuromuscular impairment following concussion.

Methods

Design and Setting

We recruited a convenience sample of 30 college-aged recreational athletes (no varsity inter-collegiate athletes were included). There were two groups (15 participants in each group): 1) Recent concussion group (median time since concussion of 126 days, range 28-432 days), and 2) Matched control group with no recent concussions. Control participants were matched to each injured participant based on sex, age (± 1 year), mass (± 10%), and height (± 5%). Participants were excluded for any of the following: attention deficit hyperactivity disorder, seizure disorders, lower extremity injury resulting in physical activity time loss of at least 3 days within the last 6 months, any history of lower extremity or low back surgery, concussion requiring admittance to the hospital, any current concussion symptoms, or a previous history of greater than 3 concussions. Additionally, we recorded the number of days since the most recent concussion in the concussed group. The Institutional Review Board at the University of North Carolina at Chapel Hill approved our study and all participants signed an informed consent document prior to testing.

Instrumentation

Vicon Nexus Three-Dimensional Motion Analysis System and Bertec Force Plates. The Vicon System (Vicon Motion Systems, Centennial, CO) consists of 10 infrared video cameras in conjunction with two piezoelectric non-conductive force platforms (Model #4060-NC Bertec Co., Columbus, OH) embedded in the floor. Each participant was outfitted with 20 individual retro-reflective markers affixed to the skin or spandex over the jugular notch, the tip of each shoulder, the L5 area of the low back, bilaterally on the anterior-superior iliac spine of the pelvis, greater trochanter, medial epicondyle of the femur, lateral epicondyle of the femur, medial malleolus, lateral malleolus, first metatarsal head, and fifth metatarsal head. Cluster markers were affixed over the sacrum and bilaterally on each thigh, shank, and foot. Left side clusters consisted of 4 retro-reflective markers while the right side and sacral clusters consisted of 3 markers. Following an initial static trial, all individual markers except those at the tip of each shoulder and jugular notch were removed and the participant completed the testing with the clusters. Kinematic data were collected at 150 Hz and calibrated for a 4m long x 3m wide x 2.5m high volume while kinetic data were collected at 1500 Hz. All video data will be time synchronized with the analog force plate data. The world axis system was established as positive anteriorly in the sagittal plane, left in the frontal plane, and superior in the transverse plane.

Data Collection Procedures

Participants reported to the laboratory for a single testing session and completed 3 functional movement tasks. The order of the tasks was randomized for each participant. Participants were given multiple practice trials for each task until they reported feeling comfortable. All functional tasks are described below.

Jump Landing. Participants stood on a 30 cm box placed a horizontal distance equal to 50% of their height behind the force plates. The participants were instructed to “get set,” meaning they were to take an athletic stance upon the box and await a stimulus to signal the beginning of the trial. A visual stimulus (green light) placed approximately 3 m in front of the participant was triggered randomly within 5 seconds by the investigator, indicating the start of the trial. The participant jumped forward off the box (told to “jump out, not up”) and performed a double-leg landing with the right foot in contact with one force plate and the left foot in contact with the other force plate before jumping vertically for maximal height. The participant was instructed to initiate the movement as quickly as possible following the visual stimulus. Each participant completed 5 jump landings.

Anticipated Cut. All procedures for the anticipated cut were identical to those for the jump landing with the exception of the task that was performed. Once the stimulus was provided, the participant jumped forward off the box (told to “jump out, not up”) and landed on a single leg. Immediately upon landing, the participant cut at a 45° angle in the direction provided by the investigator prior to the trial (cut towards dominant = land on non-dominant foot, cut towards non-dominant = land on dominant foot). Each participant completed 5 trials cutting in each direction (10 total trials).

Unanticipated Cut. All procedures for the unanticipated cut were identical to those for the anticipated cut. The exception was the participant was not informed which direction to cut. As the participant jumped from the box, they triggered a timing gate set at 0.76 m behind the force plates. This distance was chosen to maximize the time each participant would have to react to the directional stimulus, but be in a position where shorter participants would not be excluded. For example, participants who were approximately 1.5 m tall or less would be standing in the path of the timing gate and would therefore be unable to complete the unanticipated cut. This timing gate triggered a visual stimulus (set of blue and green lights) to the participants left or right. Participants were instructed to cut towards the light in the same manner as the anticipated cutting task above (cut towards dominant = land on non-dominant foot, cut towards non-dominant = land on dominant foot). Each participant completed 10 total trials, regardless of whether or not they were performed correctly. Trials were discarded if the participant did not land appropriately on a single leg or cut in the wrong direction.

Data Reduction and Analysis

All kinematic and kinetic data were imported into Motion Monitor v8.0 (Innovative Sports Training Inc., Chicago, IL) to calculate Euler joint angles. Joint motion was defined as the distal segment moving relative to the proximal segment, except trunk motion in the frontal and sagittal planes, which was defined as trunk segment movement relative to the vertical axis. Positive in the sagittal plane indicates flexion at the trunk and knee, and extension at the hip. Positive in the frontal plane indicates adduction at the hip, varus angle at the knee, and right lateral trunk flexion. All kinematic data were filtered with a fourth-order low-pass Butterworth filter with a cutoff frequency of 10 Hz. Kinetic data were used to determine initial ground contact (>10 N vertical ground reaction force). Data were then exported to custom Matlab software to identify all dependent variables of interest.

Position of the bottom sacral cluster marker in the sagittal and transverse planes was analyzed for 0.5 seconds prior to onset of the visual stimulus. The mean position of the marker was calculated in each plane. First movement during jump landing, anticipated cutting, and unanticipated cutting was defined as the first movement of the bottom sacral cluster marker in either the sagittal or transverse plane exceeding 3 cm from the mean marker position prior to the visual stimulus onset. Visual inspection of the data showed some participants moved in the sagittal plane first, while others first moved in the transverse plane. Thus, we analyzed both the sagittal and transverse planes in order to capture first movement after presentation of the visual stimulus. Reaction time was defined as the time in seconds from visual stimulus onset to first movement.

Reaction time cost (RTC) has not been previously validated in the literature. Reaction time cost is modeled after the previously validated dual-task cost formula and is calculated as presented below.

$$\text{Reaction Time Cost} = \left[\frac{\left(\text{Reaction Time}_{\text{Cut}} - \text{Reaction Time}_{\text{Jump Landing}}\right)}{\text{Reaction Time}_{\text{Jump Landing}}}\right] x\ 100$$

Eq. 1

This formula allows for comparison between participants and groups as it standardizes participant scores by baseline performance. In the case of RTC, baseline performance will be the reaction time recorded for the simplest task, the jump landing. We initially compared reaction time during anticipated cuts to the dominant and non-dominant sides utilizing a paired samples t test. No between cut direction differences were observed ($t_{27}=0.84$; $p=0.410$), so we combined reaction time outcomes for cuts to the dominant and non-dominant side. Because 5 jump landing trials were performed, we used the first 5 successfully completed anticipated and unanticipated cuts (out of 10 total trials) when analyzing reaction time and RTC.

Trunk, hip, and knee joint angles at initial ground contact were calculated in the sagittal and frontal planes during jump landing, anticipated cut, and unanticipated cut. Initial ground contact was defined as greater than 10 N of vertical ground reaction force. Dependent variables for jump landing are reported as angles of the dominant limb. When assessing joint angle outcomes, cuts toward the dominant and non-dominant sides were analyzed separately.

To explore reaction time outcomes, we utilized a 3 (condition) x 2 (group) between subjects mixed-model analysis of covariance (ANCOVA). We covaried for the number of days between the last concussion and the testing session in all statistical models. The number of days post-injury for each concussion group participant was subtracted from the group mean days since concussion (177 days). Control participants were assigned a value of zero days since concussion. This created a mean centered days since concussion value, which was used as a covariate in all statistical models. An a priori alpha value of 0.05 was established.

Reaction time cost was calculated separately for anticipated cut and unanticipated cut conditions. In both cases, reaction time values were compared back to jump landing reaction time values (see Eq. 1 presented above). Positive values for reaction time cost indicate increased reaction time during cut trials as compared to jump landing trials.

Results

As previously reported in manuscript 1, independent t tests comparing demographics revealed no statistically significant group differences. Reaction time data were not available for 2 concussed group participants due to data collection issues with the visual stimulus. Twenty-seven of the thirty participants successfully completed at least 1 unanticipated cut towards their non-dominant side. All thirty participants were used to investigate all other outcomes.

Reaction Time. There were no significant interactions observed for reaction time ($F_{2,52}$=2.51; p=0.091). We observed a significant main effect for task ($F_{2,52}$=15.10; p<0.001) such that slower reaction times were observed during unanticipated cut (0.552 s; 95% CI: 0.525-0.579) as compared to both anticipated cut (p<0.001; ES=1.04; anticipated cut mean=0.486 s; 95% CI: 0.458-0.513) and jump landing (p=0.020; ES=0.53; jump landing mean=0.518 s; 95% CI: 0.491-0.545). Additionally, jump landing reaction times were significantly slower than anticipated cut reaction times (p=0.031; ES=0.50). Group by task reaction time descriptive statistics and effect sizes are presented in **Table 8**.

Reaction Time Cost. Significant group differences were observed during anticipated cut ($F_{2, 25}$=5.26; p=0.030) such that the control group reaction time cost (10.7%) was significantly better than the concussed group (0.8%). No group differences were observed for RTC during the unanticipated cut ($F_{2, 25}$=1.06; p=0.313). Group by task reaction time cost descriptive statistics and effect sizes are presented in **Table 8**.

Biomechanical Outcomes. There were no group differences during the jump landing task (p≥0.236). Jump landing outcomes and effect sizes are presented in **Table 9**. The concussed group displayed significantly greater trunk flexion as compared to the control group when cutting towards the non-dominant side during the anticipated cutting task ($F_{2, 27}$=5.89; p=0.022). No other comparisons were statistically significant (p≥0.079). Anticipated cutting outcomes and effect sizes are presented in **Table 10** while unanticipated cutting outcomes and effect sizes are presented in **Table 11**.

Discussion

Functional assessments of dynamic, sport-like movement are not a part of the recommended concussion assessment battery.[19, 29] However, reports of dynamic balance deficits,[17, 50, 61] cortical hypoexcitability,[21, 111] and increased risk of musculoskeletal injury[12-14, 26] suggest that there may be motor control effects secondary to concussion that persist beyond return to play. The findings from this preliminary study suggest there may be differences in reaction time and trunk control during sport-like dynamic movement. Healthy participants tended to be more flexed at the trunk during cutting tasks (ES between 0.32-0.63; mean difference 2.5 to 5.1°). When standardizing for reaction time during our simplest task (jump landing) using the reaction time cost formula, we observed significantly better reaction time cost during anticipated cut for the control group as compared to the concussed group (ES=0.62). However, our findings must be regarded as tentative. Our sample size was small, and our design was cross-sectional. We cannot eliminate the possibility that these observed group differences existed prior to the onset of concussion. This study is intended to be a preliminary investigation with the goal of informing the design of larger studies that include baseline pre-injury measures as well as serial measures throughout recovery.

It is important to note we failed to reject the null hypotheses of no group differences for the majority of our comparisons. There may be several reasons for this. Our concussed group was about 4 months post-injury (median time since concussion 126 days, range 28-432 days) when we assessed their movement. If there were movement differences acutely after concussion, they may have resolved by the time we collected data. Second, we observed a relatively small sample, potentially limiting our statistical power and increasing our chances of making a type II error. Despite these limitations, this is the first study to examine functional movement outcomes post-concussion. Although the findings currently have limited clinical applicability, this study demonstrates the feasibility of a, functional movement testing protocol among athletes before concussion (healthy baseline) and then serially 1-14 months post-concussion. A priority for future studies should be to employ a longitudinal design to determine if movement differences exist acutely after brain injury and to identify how long they remain. Although the clinical utility of our findings is unclear, understanding reaction time under research paradigms that simulate sport-specific conditions may be an important consideration in elucidating the mechanisms behind the increased risk of musculoskeletal injury after concussion.[12, 14, 26]

Reaction time (i.e., cognitive processing speed) is commonly assessed following concussion as part of a neurocognitive test battery. Many computerized cognitive tests assess reaction time using various tasks by adapting traditional neuropsychological tests such as the Stroop Task and symbol matching. Although the outcome variable may vary slightly, two examples are when participants must click their mouse when presented with words where the font color is congruent with the word (i.e. the word ‘red’ written in red colored text, congruent Stroop, simple reaction time) or when the font color is incongruent with the word (i.e. the word ‘red’ written in green colored text, non-congruent Stroop, complex reaction time). The time between presentation of the stimulus and clicking of the mouse is recorded as the reaction time. These measures have been shown to be sensitive to concussion in the acute phase of the injury.[44, 69]

Whether post-concussion deficits in cognitive processing speed on neuropsychological tools manifests in more functional activities, such as a delayed movement response during competitive sports, is not clear. A more functional reaction time measure has recently been developed and has demonstrated sensitivity to acute concussion reaction time deficits.[24, 72, 73] To assess reaction time using this tool (published as the Reaction Time Clinical), the examiner drops a hockey puck affixed to a long stick. The patient catches the stick as fast as they can, and the examiner records the distance from the hockey puck where the patient catches the stick. This is repeated several times, and a reaction time is calculated. This is a valid and clinician friendly tool to assess movement reaction time. However, these measures are very simplistic, and do not present athletes with the requisite challenge to mimic the on-field stimuli for which they will need to respond once they return to participation. It remains unclear how these simplistic reaction times measures correlate to the reaction time required to appropriately respond to external stimuli during sport activity. Future studies should quantify differences between various reaction time measures (static and dynamic assessments) to ensure clinicians are appropriately assessing reaction time deficits following concussion. Determining relationships between traditional reaction time assessment tools and more functional reaction time assessments (as employed here) is important to determine if reaction time needed for peak performance during athletic participation can be predicted by traditional reaction time assessments.

We developed novel methods to explore functional reaction time in the current study. A classic study by Henry and Rodgers[112] details the influence of task complexity on reaction time. In short, as overall task difficulty increases, so does reaction time. We sought to manipulate task difficulty through 3 movement tasks. We hypothesized reaction times would be slowest during the most difficult motor task, the unanticipated cut. On the other hand, we felt reaction times would be fastest during the simplest motor task, the jump landing. Our hypothesis was partially supported, as participants had significantly slower reaction times during the unanticipated cut as compared to both the anticipated cut and jump landing. Interestingly, participants demonstrated faster reaction times during anticipated cutting as compared to jump landing. It is possible the slower reaction times during jump landing were due to the task being too simple. In the context of balance studies, several studies reveal better balance when a simple cognitive task is added to the balance task instead of the balance task alone.[113-115] In this situation, the simple cognitive task serves to distract the participant from the balance task at hand. If the balance task is simple enough, participants often perform better when their attention is diverted away from the relatively simple act of maintaining postural control. Reaction time may be similarly influenced by attention demand. Participants may have focused their attention on the reaction time component of the jump landing because the motor task was simple. Thus, it is plausible reaction time may actually have suffered due to the increased attentional demand, just as balance has suffered with increased attentional demand as discussed above. In contrast, attention may have been diverted to the motor portion of the anticipated cutting task, making the reaction portion of the movement less reflexive. Reaction time should be explored further following concussion during more dynamic movements, such as counter movements, multiple cutting tasks, and jump/cut combination tasks. Developing a movement task that maximally stresses neuromuscular control and reaction time in laboratory conditions may shed light on functional movement reaction time deficits following concussion. Future research should build on these paradigms. Influencing reaction time by manipulating task difficulty may have implications for assessing and rehabilitating concussion.

We developed a novel measure of reaction time, reaction time cost, and hypothesized that it would be sensitive to reaction time deficits in recently concussed individuals; specifically, that reaction time would be greater in individuals with concussion history than individuals without concussion history. The reaction time cost calculation uses reaction times measured during difficult movement tasks, such as cutting, and normalizes them to reaction time on easier movement tasks, such as jump landing. Accounting for performance on the simplest movement task allows for identification of improvement or decline on subsequent movement tasks on an individual level. Although we cannot draw definitive conclusions from the current data, reaction time cost may have value for future investigations into reaction time following concussion, especially in longitudinal study designs aimed at observing reaction time at multiple points along the recovery trajectory following concussion.

We observed small but statistically significant between group differences in trunk flexion at initial ground contact. Further examination of biomechanical outcomes during functional movement after concussion is warranted. We only report joint angles at initial ground contact. These variables were chosen as they are predictive of musculoskeletal injury.[79, 80, 82] We sought to identify differences between healthy and recently concussed participants, but are currently unable to say if the differences observed in trunk flexion during anticipated cutting influence injury risk. Increased trunk flexion is associated with increased knee and hip flexion angles as well as a decreased risk of ACL injury,[82] but too much knee flexion has been associated with a higher prospective rate of ACL injury.[80] It is important to note the trunk flexion described in this previous study was, on average, over 40 degrees.[80] In our sample, mean trunk flexion angles were less than 30 degrees for both groups. Thus, it is unlikely that the statistically significant group differences we observed are of clinical significance. Longitudinal studies and cross-sectional studies in more acutely injured populations are needed to better understand how movement patterns may be affected following concussion, and whether alterations in movement patterns after concussion are risk factors for future injury. Finally, more in-depth biomechanical analysis beyond joint angles may be warranted to more fully understand the potential value of joint kinetics in functional movement assessment following concussion.

Conclusion

The exact mechanism for increased risk of musculoskeletal injury following concussion is yet to be elucidated. Our findings suggest it is possible that there are subtle reaction time and trunk control differences between recently concussed and healthy individuals. The observed differences may reflect increased cortical hypoexcitability and altered neuromuscular control following brain injury that persist beyond return to participation, but these mechanisms needs to be empirically tested in future research.

Table 8. Reaction time and reaction time cost (RTC) during jump landing, anticipated cut, and unanticipated cut, adjusted for days since concussion.

Task	**Group**		**P value**[a]	**Effect Size**[b]
	Mean (95% CI)			
	Concussion	**Control**		
Jump Landing	0.517 (0.471, 0.551)	0.5195 (0.482, 0.557)	0.091	0.02
Anticipated Cut	0.511 (0.471, 0.551)	0.461 (0.424, 0.498)		0.35
Unanticipated Cut	0.569 (0.529, 0.608)	0.536 (0.499, 0.573)		0.23
Anticipated Cut RTC	-0.82% (-7.29, 5.65)	-10.68% (-16.70, -4.66)	0.030	0.62
Unanticipated Cut RTC	10.06% (2.62, 17.50)	4.97% (-1.95, 11.90)	0.313	0.28

[a] All statistical models covaried for the mean centered number of days between concussion and testing session. P value for the 3 movement tasks represents the interaction term in a 3 (task) x 2 (group) ANCOVA. P value for the RTC outcomes represents between group comparison, one for anticipated cut RTC and one for unanticipated cut RTC. [b] Effect size calculated as Cohen's *d*. Reaction time cost calculated as: ((Cut - Jump Landing) / Jump Landing) x 100. CI = confidence interval, RTC = reaction time cost. Data were missing for 2 concussed group participants.

Table 9. Trunk, hip, and knee angles (°) at initial ground contact for each group during jump landing, adjusted for days since concussion.

	Group Mean (95% CI)		**P value**	**Effect Size**[a]
	Concussion	**Control**		
Jump Landing[b]				
Trunk Sagittal	28.5 (25.0, 32.0)	25.6 (22.2, 29.1)	0.236	0.31
Trunk Frontal	0.1 (-0.7, 1.0)	-0.1 (-1.0, 0.7)	0.651	0.12
Hip Sagittal	-32.4 (-37.5 -27.2)	-33.9 (-39.0, -28.7)	0.680	0.11
Hip Frontal	-8.9 (-11.6, -6.3)	-7.9 (-10.6, -5.3)	0.596	0.14
Knee Sagittal	27.0 (23.7, 30.3)	26.9 (23.5, 30.2)	0.956	0.01
Knee Frontal	1.8 (-0.8, 4.4)	1.4 (-1.2, 4.0)	0.823	0.06

[a] Effect size calculated as Cohen's *d*. [b] Angles at hip and knee are calculated for each participants dominant side. Positive in the sagittal plane indicates flexion at the trunk and knee, extension at the hip. Positive in the frontal plane indicates adduction at the hip, varus angle at the knee, and right lateral trunk flexion. CI = confidence interval.

Table 10. Trunk, hip, and knee angles (°) at initial ground contact for each group during anticipated cut, adjusted for days since concussion.

	Group Mean (95% CI)		**P value**	**Effect Size**[a]
	Concussion	**Control**		
Dominant Cut[b]				
Trunk Sagittal	26.9 (24.2, 29.6)	23.5 (20.8, 26.2)	0.079	0.47
Trunk Frontal	-0.2 (-2.0, 1.6)	-0.5 (-2.2, 1.3)	0.819	0.06
Hip Sagittal	-21.0 (-24.8, -17.3)	-21.1 (-24.9, -17,4)	0.965	0.01
Hip Frontal	-16.5 (-20.4, -12.6)	-15.3 (-19.2, -11.3)	0.648	0.12
Knee Sagittal	11.8 (9.5, 14.1)	12.1 (9.8, 14.4)	0.855	0.05
Knee Frontal	-0.5 (-2.8, 1.7)	-1.0 (-3.3, 1.2)	0.763	0.08
Non-Dominant Cut[c]				
Trunk Sagittal	27.1 (24.1, 30.2)	22.0 (18.9, 25.1)	0.022	0.63
Trunk Frontal	0.0 (-1.3, 1.4)	1.7 (0.3, 3.0)	0.087	0.46
Hip Sagittal	-18.3 (-22.5, -14.1)	-18.9 (-23.1, -14.7)	0.844	0.05
Hip Frontal	-19.1 (-23.2, -15.0)	-15.3 (-19.4, -11.2)	0.191	0.35
Knee Sagittal	11.7 (9.1, 14.2)	11.1 (8.6, 13.7)	0.762	0.08
Knee Frontal	0.7 (-1.9, 3.2)	-2.2 (-4.8, 0.3)	0.115	0.23

[a] Effect size calculated as Cohen's *d*. [b] Indicates a cut towards the dominant side, executed by planting on the non-dominant foot. [c] Indicates a cut towards the non-dominant side, executed by planting on the dominant side. Positive in the sagittal plane indicates flexion at the trunk and knee, extension at the hip. Positive in the frontal plane indicates adduction at the hip, varus angle at the knee, and right lateral trunk flexion. CI = confidence interval.

Table 11. Trunk, hip, and knee angles (°) at initial ground contact for each group during unanticipated cut, adjusted for days since concussion.

	Group Mean (95% CI)		P value	Effect Size[a]
	Concussion	**Control**		
Dominant Cut[b]				
Trunk Sagittal	26.0 (23.2, 28.9)	23.3 (20.4, 26.1)	0.175	0.36
Trunk Frontal	-0.2 (-2.3, 2.0)	-1.9 (-4.0, 0.3)	0.263	0.30
Hip Sagittal	-15.8 (-19.7, -11.9)	-18.1 (-22.0, -14.2)	0.404	0.22
Hip Frontal	-17.5 (-21.4, -13.5)	-17.6 (-21.5, -13.7)	0.961	0.01
Knee Sagittal	10.8 (8.2, 13.4)	10.2 (7.6, 12.8)	0.755	0.08
Knee Frontal	-1.2 (-3.4, 1.1)	-1.5 (-3.8, 0.8)	0.833	0.06
Non-Dominant Cut[c]				
Trunk Sagittal	26.5 (23.5, 29.5)	24.0 (20.9, 27.1)	0.234	0.32
Trunk Frontal	1.7 (-1.1, 4.5)	0.8 (-2.1, 3.7)	0.645	0.12
Hip Sagittal	-16.1 (-20.6, -11.6)	-17.0 (-21.7, -12.4)	0.765	0.08
Hip Frontal	-20.6 (-24.4, -16.9)	-16.5 (-20.4, -12.6)	0.130	0.42
Knee Sagittal	11.5 (8.4, 14.6)	11.8 (8.5, 15.0)	0.896	0.03
Knee Frontal	0.6 (-2.3, 3.5)	-2.5 (-5.5, 0.5)	0.139	0.24

[a] Effect size calculated as Cohen's *d*. [b] Indicates a cut towards the dominant side, executed by planting on the non-dominant foot. [c] Indicates a cut towards the non-dominant side, executed by planting on the dominant side. 27 participants completed unanticipated cuts towards the non-dominant side. Positive in the sagittal plane indicates flexion at the trunk and knee, extension at the hip. Positive in the frontal plane indicates adduction at the hip, varus angle at the knee, and right lateral trunk flexion. CI = confidence interval.

CHAPTER VI: SUPPLEMENTARY RESULTS AND DISCUSSION

Beyond tandem gait and functional movement, understanding how previously concussed individuals compare to healthy individuals in other measures of dynamic balance may help inform future studies aimed at improving clinical practice. Proprioception, single leg squat dynamic balance, and time to stabilization have never been studied in context with brain injury. Preliminary data presented below are intended to inform future longitudinal studies in this area. While these data are unlikely to have an immediate effect on clinical practice, we believe these are important foundational data for future studies in this area.

Results

Proprioception. No group differences were observed in absolute knee flexion angle difference during the squatting task ($F_{2,27}$=1.97; p=0.172; concussion group mean knee flexion angle difference = 3.28°; 95% CI: 1.82-4.75); control group mean knee flexion angle difference = 4.70°; 95% CI: 3.24-6.16).

Time to Stabilization. Time to stabilization between the groups did not differ when analyzing the dominant limb ($F_{2,27}$=0.64; p=0.431; concussion group = 2.04 s; 95% CI: 1.68-2.40); control group = 1.84 s; 95% CI: 1.48-2.20), but the concussed group (1.90 s; 95% CI: 1.69-2.11) took significantly longer to stabilize than the control group (1.56 s; 95% CI: 1.35-1.76) during non-dominant limb time to stabilization ($F_{2,27}$=5.69; p=0.024; ES=0.62). Time to stabilization values are presented in **Figure 5**.

Single Leg Squat. No significant differences were observed for any of the outcomes measured during the single leg squat task ($p \geq 0.197$). All descriptive statistics and statistical comparisons during single leg squat are presented in **Table 12**.

Discussion

Numerous studies have suggested dynamic balance deficits during gait may persist beyond athlete return to play following concussion.[18, 62, 116] These deficits may be contributing to increased musculoskeletal injury risk following concussion,[12-14, 26] but more research is needed into functional aspects of movement. Our findings suggest time to stabilization following a single leg hop may be able to distinguish between those who have recently suffered a concussion as compared to healthy control subjects.

Previous research has identified time to stabilization deficits in individuals suffering chronic ankle instability,[58] individuals with recent ACL injury,[117] and female athletes an average of 2.5 years post-ACL reconstruction.[108] While static balance is commonly assessed during concussion recovery,[19] more dynamic balance assessments are not as common. Time to stabilization may allow for a more comprehensive assessment of postural control system performance in environments that more closely mimic those the athlete will experience during sport. Importantly, our observed time to stabilization deficits suggest there may be lingering neuromuscular control deficits that persist beyond traditional athlete return to play. Our preliminary investigation was the first to explore time to stabilization in recently concussed individuals. We believe our findings underscore the need for further longitudinal studies in this area. Understanding how dynamic balance outcomes, like time to stabilization, are affected acutely after injury along with their recovery course may positively influence clinical practice.

We did not find any group differences when assessing center of pressure during single leg squat. The single leg squat may not challenge the postural control system to a degree required to observe between group differences, especially in our study where the injured group was tested an average of 177 days after concussion. Future work should consider adding a cognitive component to the single leg squat task, as dynamic balance deficits appear to be more pronounced following concussion under dual-task conditions.[28, 56]

Several limitations should be discussed in the context of our findings. We observed wide variability in the time between concussion and testing session, which could skew our results. This variability was controlled for in our statistical analyses. Some of our measures may be affected by pre-existing conditions, such as chronic ankle instability. While our exclusion criteria included items designed to eliminate participants with musculoskeletal or central nervous system issues that could affect one or more of our outcomes, it is possible participants had conditions we were unaware of at the time of testing. Our sample is relatively small such that our findings should be confirmed in more prospective, larger scale investigations.

Recently concussed individuals took longer to stabilize during a single leg hop task on their non-dominant limb. The clinical utility of our findings is unclear given the preliminary nature of our investigation. Researchers should develop methodology that allows for assessment of these variables acutely after injury, but also seeks to identify how dynamic balance recovers after concussion. Understanding the recovery of dynamic balance in relation to more traditional concussion assessment measures may greatly enhance the care afforded to individuals after suffering a brain injury.

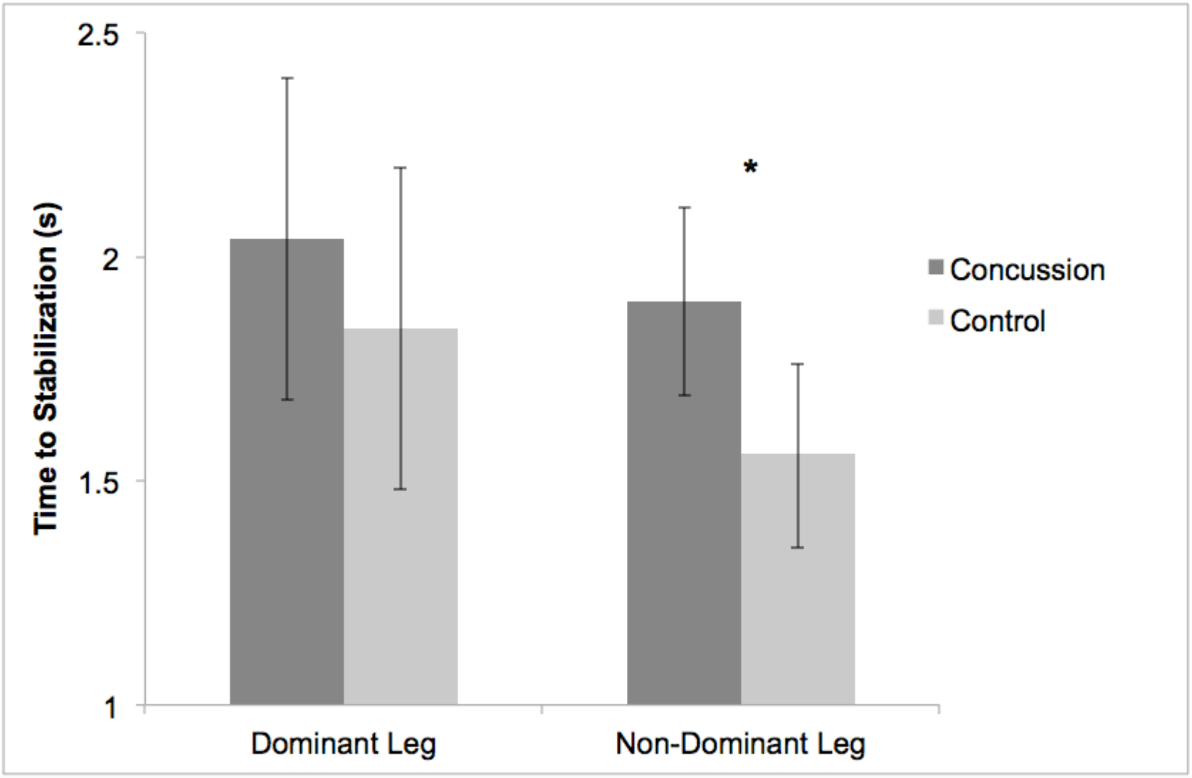

Figure 5. Time to stabilization (s) during single leg hop on the dominant and non-dominant legs between groups.
* Indicates statistically significant difference between groups ($F_{2,27}=5.69$; $p=0.024$). Error bars represent the 95% confidence intervals.

Table 12. Center of pressure (COP) and sacrum marker outcomes during single leg squat.

Outcome	**Group** Mean (95% CI) **Concussion**	 **Control**	**P value**
COP Path (cm)	84.6 (76.5, 92.7)	77.2 (69.1, 85.3)	0.197
COP Speed (cm/s)	12.2 (10.9, 13.6)	12.0 (10.6, 13.3)	0.765
Sagittal Plane Velocity (cm/s)	1.4 (1.1, 1.6)	1.4 (1.1, 1.6)	0.974
Frontal Plane Velocity (cm/s)	0.7 (0.6, 0.7)	0.7 (0.6, 0.8)	0.837
Sacrum Displacement (cm)	23.2 (21.1, 25.2)	22.8 (20.8, 24.8)	0.787
Sacrum Speed (cm/s)	3.6 (3.0, 4.1)	3.6 (3.0, 4.1)	0.987

CI = confidence interval.

CHAPTER VII: DISSERTATION SUMMARY AND CONCLUSIONS

Results Summary

We observed significantly slower tandem gait velocity in the concussed group as compared to the control group. Additionally, we observed a significantly greater center of pressure speed dual-task cost for the concussed group as compared to the control group. During the functional movement assessment, control participants demonstrated better anticipated cut reaction time cost than concussed participants while concussed participants demonstrated significantly greater trunk flexion during the anticipated cut to the non-dominant side. We also observed significantly longer time to stabilization on the non-dominant side for the concussed group as compared to the control group.

Despite these significant findings, we failed to reject the null hypothesis for the majority of our outcome measures. We observed no significant group by condition interactions for any tandem gait outcome measures, nor any between group differences in reaction time. Our biomechanical assessment revealed only a trunk flexion difference between groups during one task, while no knee or hip joint angle differences were statistically significant. We report no group differences for any outcome measures during the single leg squat balance task, and no group differences in proprioception.

Methodologic Limitations

Our investigation was intended to be a preliminary analysis of movement following concussion and is not without limitations that will need to be addressed in designing future clinical studies. As such, observed significant group differences must be interpreted in context with several methodologic limitations. We did not have baseline data for any of our dependent variables to make pre-injury to post-injury comparisons. While these data would be compelling, we felt baseline testing for this investigation was not practical at this point in our scientific knowledge of this topic. First, from a feasibility standpoint, we drew participants from a very large population and it would not have been practical to attempt to complete baseline tests on everyone. Second, while we worked to match each injured participant to a similar control participant based on age, sex, height, and mass, the relationship of these factors to TBI and human movement is complex. Given our limited sample size, it is possible our observed group differences existed prior to concussion simply because of the influence of random variation (i.e. chance). Thus, future methodology should seek to investigate these and other functional movement outcomes longitudinally, utilizing pre-injury assessments.

We investigated a cohort of recreational athletes. As such, participation in specific sports varied, and in many cases our participants reported playing multiple sports recreationally. Differences in sport training and experience could influence the dependent variables we measured. Sport-specific cohorts should be investigated and movement tasks should be developed that are specific to movements that occur more frequently in individual sports.

We examined a fairly small cohort (n=15 in each group), which could certainly affect our Type II error probability. **Figure 6** displays observed effect sizes during the anticipated cut task. To aid clinical interpretation, observed mean differences are reported in the figure as well. This figure is intended to allow the reader to clinically interpret statistically significant and non-significant findings, such as the observed difference of approximately 5° of trunk flexion. While our sample size was small, our novel methodology and unique application of these methods to recently concussed individuals is an appropriate first step in this line of research inquiry, and provides evidence of feasibility of these rigorous and innovative testing protocols for identifying dynamic balance and functional movement impairments in individuals 1-14 months post-concussion. Future work should investigate larger samples over multiple time points (starting closer to injury onset), and adding important clinical outcomes such as prospectively tracking musculoskeletal injuries. Combining gait and biomechanical outcomes with musculoskeletal injury records is the most effective way to determine the clinical applicability of our findings. For example, we do not know if our observed group difference of approximately 5 degrees of trunk flexion during the anticipated cut is clinically significant. It is certainly possible this difference does not translate to any substantial clinical outcome, but we cannot say for certain from our data. Enhanced research methods combining multiple assessment metrics is necessary to gain a complete understanding of movement maladaptations following concussion, along with their potential consequences.

Interpretation of Findings

The clinical significance of our findings is affected by the limitations discussed. Despite wide variability in time since concussion (1-14 months) in our sample, we found several statistically significant group differences. It is important to recognize there were many other non-significant group differences. This could mean there were in fact no movement differences (i.e., that the concussed group do not have performance deficits significantly greater than healthy controls in our functional tasks), or that differences initially present after injury were recovered by the time we assessed the participants. Despite this limitation, we felt our methodology was appropriate given previously described differences at and beyond 2 months after concussion.[18, 62] Future study is warranted to understand potential acute dynamic balance and functional movement maladaptations following concussion. This methodology will greatly inform the potential clinical significance of movement assessments post-concussion.

Tandem Gait Outcomes

We report a between group velocity difference during tandem walking collapsed across all conditions of approximately 0.04 m/s. While this is a small effect in the context of normal walking, a clinically important difference in tandem walking velocity has not yet been established. Because tandem gait is more challenging than standard gait, our reported average velocities are much slower than those reported during standard gait following concussion (approximately 1.20 to 1.50 m/s).[19, 28] In order to appropriately interpret our group difference in context with existing literature, standardizing by velocity may be helpful. We can accomplish this by dividing the observed group difference by the overall mean velocity, and then multiplying by 100 to obtain a proportional mean difference. Using this standardization, we observed a 15% proportional mean difference between-groups in tandem gait velocity. Previous reports of standard gait following concussion report statistically significant mean differences between-groups in velocity, but proportionately the differences are around 7 or 8%.[18, 27] While this method is useful to compare findings across different gait tasks, the clinical significance of mean differences in tandem gait velocity less than 0.05 m/s remains unclear. Future studies should attempt to include long-term outcome measures, such as musculoskeletal injury rates following concussion, which may greatly aid in clinical interpretation of standard and tandem gait outcomes following concussion. Beyond injury outcomes, including self-reported outcomes related to participant perception of balance deficiencies and the affect these deficiencies may have on quality of life will further inform the utility of a tandem gait assessment.

Additionally, the SCAT3 tandem gait task indicates participants “pass” the test if they perform tandem gait in less than 14 seconds.[19] This equates to a tandem gait velocity of approximately 0.43 m/s. Our observed average velocity during the tandem gait only condition was approximately 0.35 m/s, and this velocity decreased as the conditions increased in difficulty. We believe this finding, in conjunction with the high “fail” rate of healthy individuals,[20] underscores the lack of clinical utility of the currently recommended SCAT3 tandem gait task. Again, the clinical significance of our own findings is unclear, but it is apparent the current SCAT3 tandem gait task will not be useful in assessing concussion.

Tandem Gait and Reaction Time Outcomes

We observed mutual interference during our tandem gait tasks, such that both the cognitive and motor tasks were affected during tandem gait dual-task trials. This lends to the capacity sharing theory of dual-task interference since both tasks were still completed, but were performed less effectively. It is unlikely the same theories apply to the reaction time tasks as the methodology was different than that employed in the tandem gait protocol. During the tandem gait protocol, both the motor and cognitive tasks were continuous. This likely led to a shared attentional capacity, thereby negatively affecting both motor and cognitive task performance. Although our reaction time paradigm was designed such that the motor task would increase in difficulty, we did not employ a continuous cognitive task. It was interesting to note better reaction time during the anticipated cut as compared to the jump landing, and potential mechanisms behind this finding were discussed in Manuscript 2. Our hypothesis regarding worse reaction time as motor task difficulty increased was based on previous literature describing this phenomenon.[112] It was hypothesized the increased task difficulty would stress the ability of the participant to properly plan and execute the motor task (anticipated or unanticipated cut). During our tandem gait dual-task trials, it is more likely the attentional demands of the sum of the motor and cognitive tasks surpassed the attentional reserve of participants, resulting in mutual interference. An interesting future paradigm might employ a cognitive task in conjunction with the reaction time tasks we employed here. This may stress attentional capacity in a similar way to our tandem gait protocol, potentially affecting movement, reaction time, or a combination of the two. This type of paradigm might also better reflect the cognitive and physical demands of sport better than assessing reaction time as we did in this investigation.

Time to Stabilization Outcomes

Our reported group differences in time to stabilization also appear small. Our observed difference of approximately 0.34 s is very similar, however, to previously reported group differences between those with and without chronic ankle instability and anterior cruciate ligament reconstruction.[108, 118] This may be an important clinical finding of this dissertation. Previous research utilizing time to stabilization determined this measure was accurate in identifying those with chronic ankle instability.[118] Thus, time to stabilization has clinical utility in identifying those who may be at risk for ankle injuries prior to or during athletic participation. Programs can be designed to strengthen the ankle joint and increase proprioception with the intention of limiting acute and chronic ankle injuries. Further research into time to stabilization following concussion is important to determine if it may have similar clinical applicability. As with many of our other outcomes, understanding acute time to stabilization maladaptations and their recovery is important. Our preliminary findings lay the foundation for further longitudinal studies.

Future Directions

Our novel investigation of dynamic balance and functional movement following concussion was intended to be a preliminary investigation of these outcomes. Much more work is needed to develop a better understanding of potential maladaptations that may or may not occur after brain injury and to track their recovery course. Prospective, longitudinal investigation is imperative to identify areas of concussion recovery that may be clinically significant. Adding additional outcome variables, such as subsequent concussion and musculoskeletal injury rates, will also be important to develop a full understanding of the clinical implications of this line of research.

While these large-scale studies will be important, important incremental inquiries are needed to better understand functional movement following concussion. Assessment of reaction time has been an important piece of concussion management for over a decade, but it is commonly assessed in a very static, quiet environment by the simple interaction with a standard computer mouse. Clinically, it is important we understand what we are measuring and what limitations it may have. Does reaction time assessment via methods described above correlate with reaction time in more dynamic, sport-like environments? Future studies should attempt to quantify reaction time through various methods. These future studies will be the first step in informing the clinical utility of various reaction time measures. If static reaction time measures do not equate to dynamic reaction time measures, additional study will be needed to establish the effect of concussion on dynamic measures. Do these dynamic reaction time measures recover in the same manner as static measures following concussion? If not, what clinical consequences does that have? Again, including outcome measures related to injury and on-field performance may be important to develop a full clinical understanding of dynamic reaction time assessments.

Including baseline measures of clinical outcomes is important. This allows researchers to compare post-injury assessment scores to healthy, pre-injury scores. While this is often the preferred research methodology, our own previous work has demonstrated baseline assessments may not always add clinical value.[119] Including dynamic balance and functional movement measures in a baseline protocol will be very challenging. The data in this dissertation took approximately 2 hours per participant to collect. This is not a clinically feasible timeline. Our data suggests certain measures, such as time to stabilization, have the potential to be more useful than others post-concussion. Additionally, our novel reaction time cost formula may be important for future research. Using this formula, researchers may be able to obtain baseline reaction time during an easy movement task, such as jump landing, in a fairly short amount of time. Then, following concussion, more in-depth study could be conducted that would include reaction time measures during more sport-specific movements, like various cutting tasks. The baseline jump landing reaction time can then be input into the reaction time formula, allowing for post-injury reaction time standardization to baseline reaction time.

It is evident more study is needed to derive a clinically meaningful tandem gait assessment. Methodical and systematic inquiry initiated by the procedures employed in this dissertation project will develop the framework upon which acute tandem gait assessments following concussion can accurately be measured and analyzed, and will be necessary to inform the potential clinical utility of tandem gait assessments. We report several main effects for condition (**Figures 7** and **8**) that may be important moving forward. For example, we observed significantly greater center of pressure path length during both tandem gait with eyes closed and tandem gait with Brooks Visuospatial Task and eyes closed as compared to tandem gait and tandem gait with Brooks Visuospatial Task. There were no differences, however, between tandem gait with eyes closed and tandem gait with Brooks Visuospatial Task and eyes closed. Thus, subsequent study may consider dropping one of these conditions, as new information does not appear to be added. This is important, as establishing the most efficient protocol will enable prospective studies that include baseline data. Identifying condition differences will inform the most appropriate conditions to be included in studies where time with participants is limited, and will become doubly important when defining assessment protocols to be employed in clinical settings where physician-patient time may be limited. Further study should be conducted utilizing healthy samples to understand condition differences. Data gathered from these studies will be helpful in developing the most effective and efficient research paradigms that will include concussed participants.

Tracking recovery of tandem gait outcomes and comparing this recovery to the recovery of standard assessment measures (neurocognitive testing, static balance testing, etc.) will also be important. Including all these measures in a single, longitudinal research design will inform the clinical value added of dynamic balance assessments such as tandem gait. If recovery of dynamic balance deficits does not coincide with recovery of traditionally assessed concussion deficits, return to play protocols will have to be reexamined to ensure the best patient outcomes are achieved.

Significance

Despite the preliminary nature of our investigation, this was an important first step in assessing dynamic balance and functional movement outcomes following concussion and demonstrating feasibility of these performance measures in a post-concussion population. We acknowledge our data have limited near-term clinical applicability. Our preliminary findings, however, suggest some assessments such as dynamic reaction time and time to stabilization may be useful in the future. As discussed above, future longitudinal methodology should seek to investigate these and similar outcomes at multiple time points following injury. Including other important outcome measures such as subsequent concussion and musculoskeletal injury will better inform the significance of dynamic balance and functional movement assessments following concussion. Our findings alone do not suggest a need to modify current concussion assessment batteries. Instead, our work suggests a better understanding of dynamic balance and functional movement outcomes is necessary, and that this work may be most valuable if conducted in individuals who are closer to injury onset. We cannot say what effect our observed differences in tandem gait velocity, reaction time cost, or time to stabilization have on clinical outcomes, but instead suggest further understanding is needed to establish clinical significance. We hope that these preliminary findings inform the development of future research paradigms aimed at developing a more comprehensive understanding of dynamic balance and functional movement following concussion.

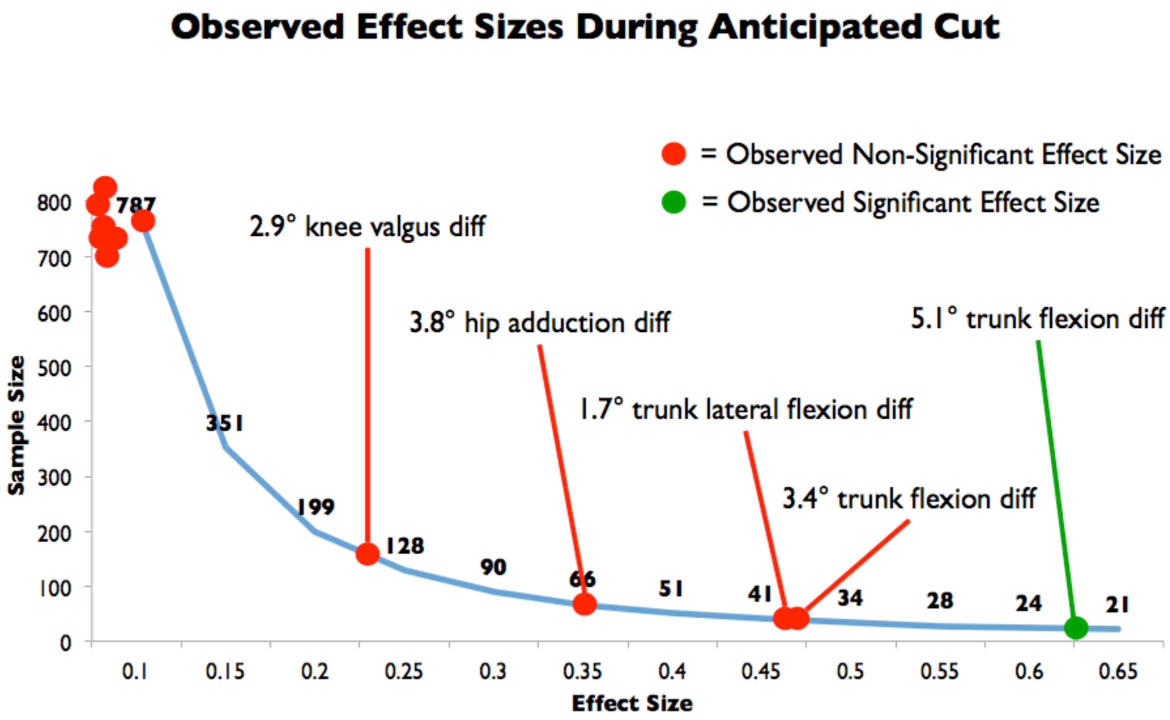

Figure 6. Observed effect sizes during anticipated cut.
Red circles indicate observed effect sizes that were not statistically significant, while green circles indicate observed effect sizes that were statistically significant. Additionally, mean differences are displayed for selected effect sizes to indicate the clinical difference in observed joint kinematics.

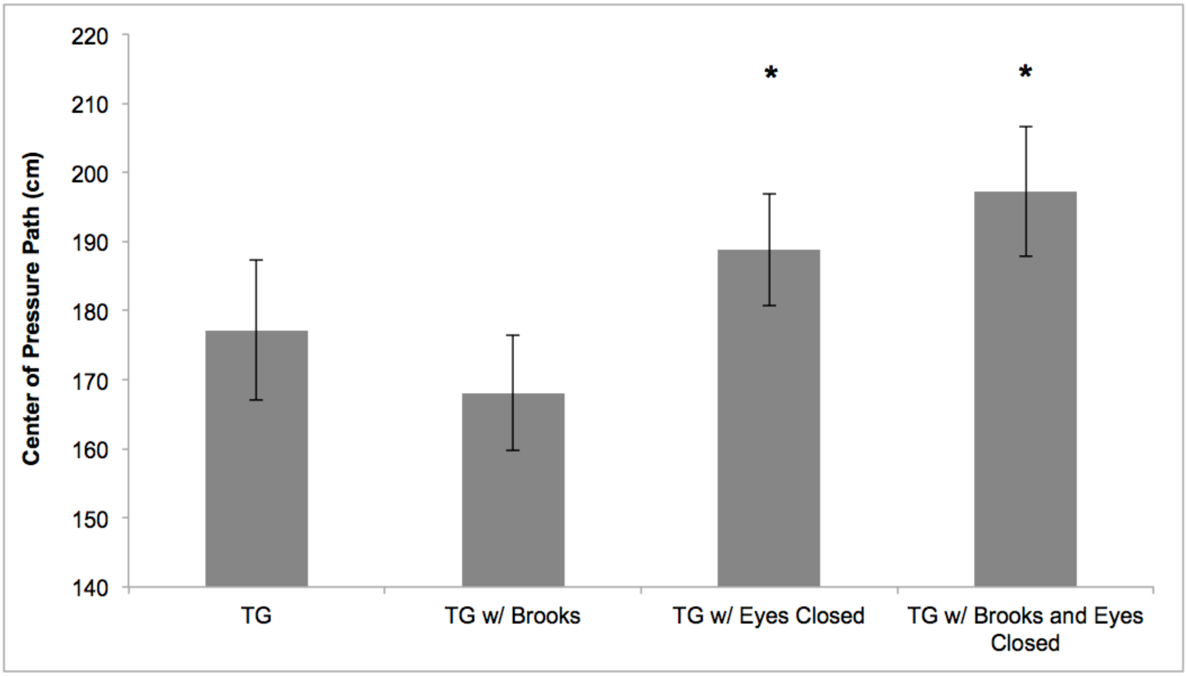

Figure 7. Center of pressure path (cm) main effects for condition.
* Indicates statistically greater center of pressure path as compared to Tandem Gait with Brooks Visuospatial Task and Tandem Gait. Error bars represent 95% confidence intervals. Values presented are adjusted for tandem gait velocity and concussed group days since concussion. TG = Tandem Gait; Brooks = Brooks Visuospatial Task.

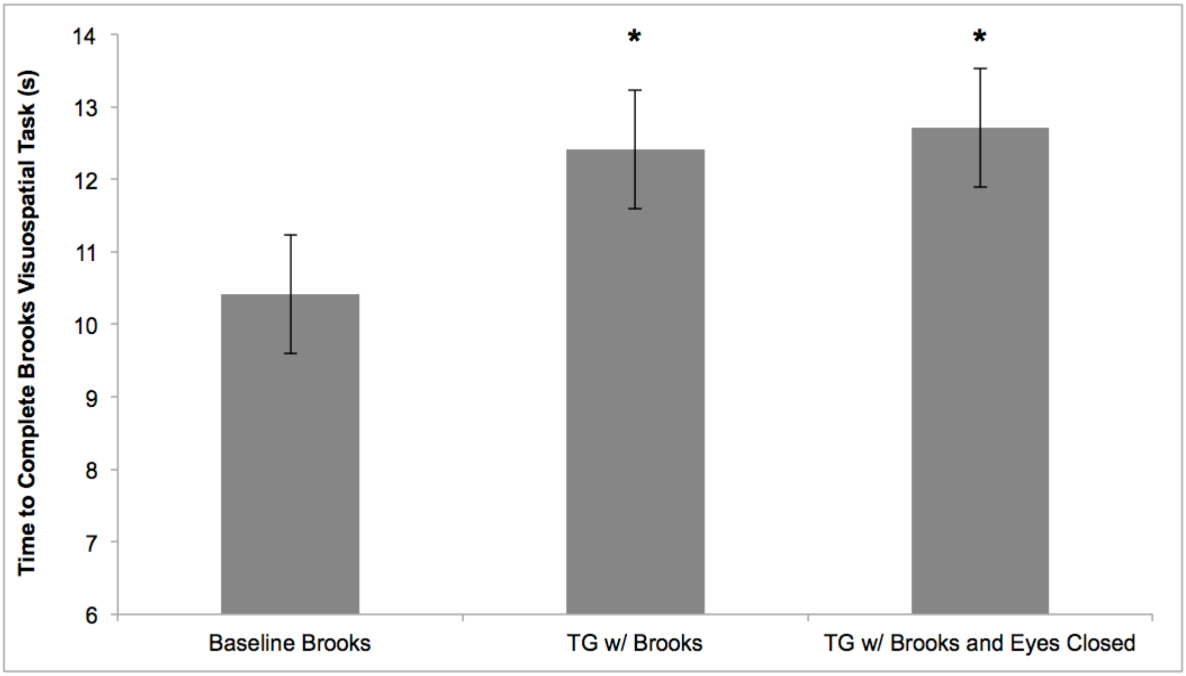

Figure 8. Time to complete Brooks Visuospatial Task (s) main effects for condition.
* Indicates statistically greater time as compared to Baseline Brooks Visuospatial. Error bars represent 95% confidence intervals. Values presented are adjusted for concussed group days since concussion. TG = Tandem Gait; Brooks = Brooks Visuospatial Task.

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