CLINICAL IMPLICATIONS OF DYNAMIC POSTURAL CONTROL IMPAIRMENTS FOLLOWING CONCUSSION

by

Jessie Reid Oldham

A dissertation submitted to the Faculty of the University of Delaware in partial fulfillment of the requirements for the degree of Doctor of Philosophy in Applied Physiology

Spring 2018

CLINICAL IMPLICATIONS OF DYNAMIC POSTURAL CONTROL IMPAIRMENTS FOLLOWING CONCUSSION

by

Jessie Reid Oldham

Approved: ____
John J. Jeka, Ph.D.
Chair of the Department of Kinesiology and Applied Physiology

Approved: ____
Kathleen S. Matt, Ph.D.
Dean of the College of Health Science

Approved: ____
Ann L. Ardis, Ph.D.
Senior Vice Provost for Graduate and Professional Education

I certify that I have read this dissertation and that in my opinion it meets the academic and professional standard required by the University as a dissertation for the degree of Doctor of Philosophy.

Signed: ____

Thomas A. Buckley, Ed.D.
Professor in charge of dissertation

I certify that I have read this dissertation and that in my opinion it meets the academic and professional standard required by the University as a dissertation for the degree of Doctor of Philosophy.

Signed: ____

Jeremy R. Crenshaw, Ph.D.
Member of dissertation committee

I certify that I have read this dissertation and that in my opinion it meets the academic and professional standard required by the University as a dissertation for the degree of Doctor of Philosophy.

Signed: ____

Christopher A. Knight, Ph.D.
Member of dissertation committee

I certify that I have read this dissertation and that in my opinion it meets the academic and professional standard required by the University as a dissertation for the degree of Doctor of Philosophy.

Signed: ____

David R. Howell, Ph.D.
Member of dissertation committee

ACKNOWLEDGMENTS

There are a number of people who made the completion of this dissertation possible. I would first like to thank my advisor, Dr. Tom Buckley, for his constant guidance over the last six years. I never imagined what started as a spur of the moment decision to do a thesis at UNC Charlotte would develop into what it has today. He has challenged me to be a better researcher, and I am extremely thankful for his support through the years. I would also like to thank my dissertation committee, consisting of Dr. Jeremy Crenshaw, Dr. Chris Knight, and Dr. David Howell for their tremendous amount of support throughout the dissertation process. They served as a great inspiration for me throughout this process, and my project would not be what it is without them.

A strong support system is critical throughout the dissertation process, and my fellow graduate students have been nothing short of amazing in helping me through all the ups and downs. There are so many who have helped me both directly and indirectly, but I especially have to thank Andrea DiTrani, Jaclyn Caccese, Aaron Struminger, Sophie Guderian, Bryce Muth, Micah Josephson, Katie Breedlove, and Kelsey Bryk for the tremendous amount of support over the years. They have not only been fellow graduate students, but also wonderful friends throughout this entire process. I would also like to thank Caroline Howard for her tremendous amount of work in helping my last aim come together.

Most importantly, I would have never made it through the last four years without the unwavering support of my close friends and family. There were many days when the finish line seemed out of reach, many days when I struggled to feel like I was good enough to be successful, and many days when I just wanted to give up. My friends and family have been there every step of the way, to pick me back up with every stumble, and I am forever grateful. Thank you in particular to Melissa DiFabio, who started out as a fellow grad student and quickly turned into my roommate and best friend. These years at Delaware would not have been the same without you, and I am forever thankful for your friendship. To my Wolfpack: Lauren, Candace, Katie, and Natalie, thank you for always keeping me inspired and putting a smile on my face, even from states away. Last but not least, to my incredible family, there are no words that do you justice. Kirk, Anita, Ashley, Daniel, and Brad: I would not be who I am today without your unyielding love and support. I am grateful to call you my family today and always.

TABLE OF CONTENTS

Appendix

LIST OF TABLES

LIST OF FIGURES

ABSTRACT

BACKGROUND: Concussions have been classified as a significant health problem and are a potential risk to an individual across the entire lifespan. Impaired postural control is a cardinal symptom following concussion, but current clinical post-concussion assessments (e.g., BESS) have poor sensitivity and specificity for identifying appropriate impairments in dynamic postural control. Conversely, gait related challenges have successfully identified both acute and lingering postural control impairments following concussion. These impairments have traditionally been elucidated through the use of sophisticated motion capture instrumentation that is not feasible for most clinical settings; thus, there is a need for postural control assessments that are more clinically feasible. Furthermore, impaired postural control has been hypothesized as a potential factor in the elevated risk of subsequent musculoskeletal injury following concussion; however, the true underlying mechanism is still unknown. **PURPOSE:** Therefore, the purpose of this study was threefold: 1) utilize an instrumented dynamic battery to identify postural control impairments across the typical concussion clinical recovery timeline, 2) determine the efficacy of tandem gait as a more clinically feasible alternative to instrumented gait, 3) investigate the association between concussion and subsequent lower extremity musculoskeletal injury risk and examine the role of dynamic postural control impairments as possible determinants. **METHODS:** This study utilized the APDM Opal IMUs to evaluate changes in gait from baseline to return to play in concussed collegiate student-athletes and matched healthy controls. Linear mixed models were used to examine the gait and tandem gait variables. A Cox proportional hazard model and binary logistic regression were used to evaluate injury risk and subsequent predictors. **RESULTS:** There were no significant differences between the concussion and control groups across the recovery timeline in single task gait; however, more challenging tasks (i.e. dual-task, step initiation, turning) were able to identify group differences. Tandem gait demonstrated better overall efficacy than the BESS, which is the most commonly used post-concussion postural control assessment. The AUC for the tandem gait variables ranged from 0.717-0.723, whereas the AUC for the BESS was only 0.427 acutely post-concussion. Further, tandem gait performance was significantly worse acutely post-concussion while BESS performance remained the same. Finally, there was a 1.82x increased risk of subsequent lower extremity injury in the year following concussion, compared to those who did not sustain a concussion. In the concussion group, 91% of athletes sustained an injury in the following year, compared to only 66% of controls. There were significant differences between the injured and non-injured groups for multiple gait parameters; however, none of the gait variables demonstrated to be significant predictors for injury risk. **DISCUSSION:** These results suggest that an instrumented dynamic battery can identify postural control impairments; however, more challenging tasks may be required. Further, tandem gait appears to be a more robust assessment than the BESS in identifying post-concussion impairments; therefore, clinicians may adopt the tandem gait test, particularly during the acute window. This investigation did identify an elevated risk of subsequent lower extremity musculoskeletal injury in the year following concussion, and there were significant group differences between those who did and did not sustain and injury across multiple gait variables. Future research should continue to work toward identifying possible predictors of subsequent injury. **CONCLUSION:** Dynamic postural control impairments were observed through both instrumented and clinical gait assessments following concussion, and the athletes who displayed a conservative gait strategy were more likely to be in the group sustaining a subsequent lower extremity injury in the following year.

Chapter 1

LITERATURE REVIEW

Epidemiology of Concussion

The term concussion dates back to the 10th century, where it was first clearly described by the Arabic physician, Rhazes.[1] In modern day, the definition of concussion is still widely debated, but the most accepted definition is that a concussion is defined as a complex pathophysiological process in the brain, induced by biomechanical forces from a direct or indirect blow to the head, neck or face.[2] It is estimated that 1.6-3.8 million sports-related concussions (SRCs) occur annually in the United States; however, that number is most likely a low estimate, as 50-80% of concussions go unreported.[3] As the definition of concussion has evolved over the years, it is no longer defined by the presence of loss of consciousness (LOC).[2]

The normal rate of concussion, per athlete exposure (AE), in the NCAA is 4.47/10,000 AEs.[4] In the NCAA student-athlete population, an AE was defined as 1 student-athlete participating in 1 NCAA practice or competition where he or she was exposed to a possible injury.[4] Football is always in the spotlight when it comes to SRC, mostly due to the fact that there is higher participation in football than all other sports; however, depending on the population, it is not always the sport with the highest incidence rate. Among NCAA student-athletes, football is actually fourth on the list, behind wrestling and men's and women's ice hockey, in terms of incidence rate per athlete exposure. Men's wrestling had the highest concussion rate at

10.92/10,000 AEs, followed by men's ice hockey (7.91/10,000 AEs), women's ice hockey (7.50/10,000 AEs) and football (6.71/10,000 AEs).[4]

The incidence rate differs at the high school level, for which there are 2.5 concussions per 10,000 AEs, and where football does have the highest rate.[5] In the high school population, football had 6.4/10,000 AEs, followed by boys' ice hockey (5.4/10,000 AEs) and boys' lacrosse (4.0/10,000 AEs).[5] Similar to the definition seen in the NCAA student-athletes, an AE at the high school level was defined as 1 athlete participating in 1 practice or competitive event.[5]

In pediatric concussion cases that reported to the ED, injury due to sports accounted for 58% of those in the 8-13 year old age group and 46% of concussions in the 14-19 year old group.[6] It has been suggested that the effects of a concussion are more detrimental to a pediatric population, defined as those athletes between 5 and 18 years old, compared to collegiate or professional athletes.[7–9] Concussions sustained in youth athletics (i.e. below high school) are concerning because they will most likely have a longer competitive career than high school or collegiate athletes and thus their window during which subsequent concussions can occur is greater.[9] Delayed cognitive recovery has already been demonstrated in a high school athletic population compared to a collegiate one.[10–12] Recovery of pediatric athletes is expected to take longer than a collegiate or professional athlete;[10,13] however, the specific recovery patterns of youth athletes are not well established in the literature and warrants future research.

Biomechanically, the mechanism (i.e. linear and rotational accelerations and forces) behind a concussive injury does not differ with age.[9] It is hypothesized that the differences seen between age in the aftermath of a concussion are due to the developing brain. There are a number of characteristics in the developing brain that differ in an adult brain, such as water content, degree of myelination, metabolic rate of glucose, increased blood flow, blood volume, synapse number and elasticity of the brain's natural sutures, and any of which could play a role in the delayed recovery time of a younger athlete.[14–18]

In terms of sex differences, in sports with both males and females, that follow the same rules, females have a higher rate of concussion diagnosis than males.[4] In NCAA sports, women's soccer, women's basketball, women's lacrosse and softball all report higher overall concussion rates than their corresponding male teams, which is consistent with previous NCAA findings.[4,19] This holds true at the high school level as well, where females not only have a higher rate of concussion, but also have a greater proportion of concussions compared to other injuries.[5] It is not fully understood as to why females tend to suffer more concussions than males, but there are multiple theories, with the most common being that females have biomechanical differences in the head and neck region.[20–22] Some examples of these biomechanical differences include females having greater angular rotation and head-neck peak accelerations and displacements[20] and females having a larger ball-to-head size ratio.[21] Female athletes also tend to be smaller in size and have weaker neck muscles, which could make them more susceptible to a concussive injury.[23] It has also been suggested that female athletes may be more truthful about reporting concussive injuries than males, although the research is mixed.[24–26]

Metabolic Cascade

Physiologically, a concussion results in an energy crisis within the brain. The physiological chain reaction following a concussion includes neuronal depolarization, release of excitatory neurotransmitters, ionic shifts, changes in glucose metabolism, altered cerebral blood flow, and impaired axonal function.[27] Immediately after a concussive injury, an abrupt release of neurotransmitters and ionic fluxes occur, specifically, an efflux of potassium and influx of calcium.[27] As the amount of extracellular potassium continues to rise, neuronal depolarization is initiated and followed by a spreading neuronal suppression, which could lead to a loss of consciousness.[27,28] Intracellular magnesium levels are also immediately reduced after a concussion, which can lead to a greater influx of calcium.[27] The calcium accumulation in the mitochondria can result in decreased oxidative metabolism, and ultimately, cell energy failure.[27,28] In an effort to correct the neuronal depolarization, the sodium-potassium (Na+-K+) pump, which relies on adenosine triphosphate (ATP), dramatically increases its workload, causing a significant increase in glucose metabolism.[27,28] The increased glycolysis also leads to an increase in lactate accumulation, which sends to brain into an acidotic state, making it possibly more susceptible to a second injury.[27,28] This "hypermetabolism" results in an energy crisis within the brain due to decreased cerebral blood flow coupled with an increased need for energy.[27,28] This state of impaired metabolism persists 7-10 days following a concussive injury, which reinforces the importance of the recovery timeline.[27,28]

Although what is known about the metabolic cascade comes from an animal model, certain phases of the cascade have now been linked to specific symptoms following concussion.[28] The "spreading depression" seen following the ion flux has been linked to the migraine-type symptoms post-concussion.[27,28] The aforementioned energy crisis that occurs in the brain as a result of the mismatch between glucose metabolism and cerebral blood flow is thought to cause the period of vulnerability to a second injury.[27,28]

Signs & Symptoms of Concussion

When a concussion is suspected, signs can include one or more of the following domains: 1) symptoms- somatic (headache), cognitive (feeling in a fog), emotional (lability), 2) physical signs (LOC or PTA), 3) changes in behavior (irritability), 4) cognitive impairment (slowed reaction times), 5) sleep disturbances (insomnia).[2,29] If there is evidence of any of the domain components, a concussion should be suspected.[2] Post-concussion symptoms will manifest differently in each individual, but the most commonly reported symptoms are headache, blurred vision, confusion and "feeling slowed down."[30–32]

Following concussion, symptoms typically resolve in 5-7 days; however, approximately 10% of individuals will experience signs and symptoms past the usual time frame, and this is termed post-concussion syndrome.[33–35] Although it is not feasible to fully predict who and who will not experience a prolonged recovery, there are a few signs, following concussion, that may help to identify those individuals who could be at a great risk. In high school football players, the presentation of dizziness at the time of injury was associated with a 6.34 times increased risk of protracted recovery, which is designated as being greater or equal to 21 days.[36]

Across a high school and collegiate population, the research regarding the role of LOC and amnesia following concussion is mixed. In the aforementioned study, dizziness was a risk factor for prolonged recovery, but neither LOC nor amnesia were significant predictors.[36] At 48 hours post-concussion, student-athletes who demonstrated a poor presentation, as determined by total symptom score and composite memory score, were over 10 times more likely to have experienced retrograde amnesia following the injury and over 4 times more likely to have experienced posttraumatic amnesia.[37] There was no significant relationship between LOC and presentation, however.[37] In a similar population, acute injury severity, including LOC, amnesia and elevated symptoms, was associated with an increased risk of prolonged recovery, where LOC significantly increased the risk of a longer than normal recovery window.[38]

Concussion Underreporting

There is no way of telling when an individual is being truthful regarding post-concussion symptoms. It is estimated that ~50% of concussions go unreported, so the true concussion incidence is in reality probably much greater than statistics show.[39] As many as 53% of concussions in high school football were unreported in the 2000s, and the most common reason for not reporting was that the high school athletes did not think their injury was serious enough to report.[39] In addition to not taking the injury serious enough, the role of the coach can also be a huge factor in concussion underreporting. Following their career, collegiate athletes disclosed the main driving factor behind hiding a concussion was to not upset the coach and risk losing playing time.[40] Contrary to popular belief, it was the issue of coach approachability and fear of missing playing time, not a lack of concussion knowledge, that drove collegiate athletes to not report concussions.[40] Concussions can also go unrecognized by student-athletes. In a collegiate population, 26.1% of student athletes reported having an unrecognized concussion during their collegiate career because the major symptom was seeing stars, which is still not considered to be a concussive injury to many student-athletes.[25]

Dose-Response Relationship

There appears to be a dose-response relationship with multiple concussions; however, the literature is inconsistent. Individuals with three or more concussions are at a three times increased risk of future concussion.[31,32] In a survey of retired professional football players, those with a history of three or more concussions presented with a fivefold rate of mild cognitive impairment, compared to those without a history of concussion and a threefold rate of reported memory impairments.[41] Although three or more is the most widely associated number with dose-response, longer recovery has been associated with fewer. Acutely concussed collegiate athletes with a history of two or more concussions took longer to recover on reaction time and verbal memory, as assessed by ImPACT, than those with no history of concussion.[42] Impairments associated with multiple concussions have also been seen in the high school population.[11,43] High school athletes with a history of two or more concussions performed similarly on cognitive tasks as those athletes who were concussed in the last week.[11] Although the evidence of a dose-response relationship has been established, there is still refuting evidence. There did not appear to be any cumulative effect of concussion history on neuropsychological test scores in high school or collegiate athletes.[44–47] However, the individuals in the aforementioned studies were only tested on ImPACT, which is known to have multiple limitations.

In terms of postural control, those with a history of at least one concussion have demonstrated balance impairments, as well as a conservative gait strategy.[48–51]

Buckley et al., demonstrated that student-athletes with a history of concussion presented with a conservative gait strategy, as evidenced by slower velocity, shorter steps, wider step width and increased double support time; however, the only variable that differed between those with a history of 1-2 concussions versus 3 or more was step width.[50] Although it was acknowledged that the sample sizes were small, the differences in gait pattern observed with the varying concussion histories could be early indications of long-term postural control deficits and/or neurological impairment.[50]

Specifically, in an NCAA population, 75-91% of repeat concussions occurred within 7-10 days of the first.[32] The energy crisis within the brain following a concussive injury is thought to be the underlying cause of this period of vulnerability to a second injury. One of the major concerns during this vulnerable period is not putting an individual at risk for second impact syndrome (SIS), which is rare, but does occur. Second impact syndrome is defined as a rapid cerebral herniation following a head injury, and it can occur when an individual suffers a second head injury before initially recovering from the initial concussion.[52] The underlying pathophysiology behind SIS is thought to be an increase in intracranial pressure as a result the energy mismatch and chaotic autoregulation of the brain's blood supply.[52]

While SIS is an acute consideration of multiple concussions, there are long-term considerations as well. After examining a survey of retired professional football players, there was an association between concussion history and a prior or current diagnosis of depression later in life.[53] When compared to those retired players who did not report a history of concussion, those with concussion history of three or more concussions were 3 times more likely to be diagnosed with depression and those with a history or one or two concussions were 1.5 times more likely to have a depression diagnosis.[53] In addition, retired players with three or more reported concussions during their career had a fivefold prevalence of mild cognitive impairment and a threefold prevalence of significant later-life memory issues than those who had no reported history of concussion.[41] The major limitation to these studies investigating long-term impairments is that the results are dependent on how accurately the retired players were able to recall their concussion health history. This was combated with the use of a spouse or family survey, which again is limited by the accuracy of reporting.[41,53]

Long-Term Effects

One of the most controversial topics surrounding concussion research today, especially in the media, is whether or not concussions lead to long-term damage. The majority those who sustain a concussion (80-90%) recover within a 7-10 day time frame.[2] However, there is increasing concern regarding the effect of a concussion, or multiple concussions, on the brain over time. The first incidence of progressive neurodegeneration over time was seen in boxers in the early 1900s, and the pathology was termed dementia pugilistica, or "punch drunk syndrome."[54] Sport-related head trauma have been reported to be risk factors for the development of Parkinson's disease, dementia, such as Alzheimer's, and amyotrophic lateral sclerosis (ALS).[55,56,57] In a spousal-reported survey of former NFL players, 35.1% of the population was reported to have some form of cognitive impairment, suggesting NFL players are at risk for developing later life cognitive issues; however, the study was preliminary.[58] Conversely, in a retrospective analysis of high school football players from the 1940s and 1950s found no increased risk of developing later life Parkinson's, dementia or ALS compared to those who did not play a sport with high risk of head trauma.[59]

The most common term being thrown around today is chronic traumatic encephalopathy, or CTE. Unlike concussion and post-concussion syndrome, CTE is a neurodegenerative disease that typically develops years after the head trauma.[60] The disease is characterized by neurofibrillary tangles, and a buildup of tau proteins, similar to those seen in Alzheimer's, but CTE is unique in its distribution of the tau.[60] Clinically, CTE is associated with increased irritability, impulsivity, aggression, depression and memory loss.[61,62] Among the most controversial issues surrounding CTE is the link between the disease and suicide. A heightened risk of suicide has been listed under the clinical characteristics of CTE[61,62]; however, there is currently insufficient evidence to make a causal link between CTE and increased risk of suicide in former athletes, and further research is needed.[63]

Another controversial issue surrounding CTE is the influence of subconcussive hits and whether or not they are a factor in the development of the disease. Collegiate football players sustain approximately 1,000 subconcussive head impacts over the course of a single season, but do not demonstrate any clinically meaningful changes from preseason to postseason.[64] In a high school population, the average number of impacts recorded over the average 14 week season was 652, with variations in playing position and starting status; however, upwards of 2,000 seasonal impacts have been recorded in a high school individual.[65] The discrepancy in the number of impacts between the high school and collegiate level is thought to be a result of the difference in number of practices and games over the course of a season.[65]

Repetitive subconcussive hits over a single season do not appear to result in short-term neurologic impairment, nor do they appear to have widespread, short-term detrimental effects.[64,66] However, from a long-term perspective, post-mortem pathological changes associated with the early stages of CTE have been discovered in contact sport athletes who were never officially diagnosed with a concussion, which would make it appear that subconcussive hits could potentially play a role in the development of the disease over time.[61] Further research is necessary to elucidate the role of subconcussive impacts in the development of long-term impairments.

Concussion Assessment

A multifaceted concussion assessment battery, consisting of self-reported symptoms, cognitive and postural control exams, is recommended.[2] When compared to baseline data, the multifaceted battery is up to 96% sensitive in acutely identifying a concussion.[67]

The presence of any self-reported symptom is a contraindication for an athlete to return to play. The easiest way to evaluate an individual following a suspected concussion is through self-reported symptoms, and the most common symptom tool is the Graded Symptom Checklist (GSC).[2] The GSC is a checklist of 17 different symptoms that are rated on a 0 (no symptoms) to 6 (severe symptoms) Likert scale.[68] In collegiate football players, the mean baseline score on the GSC was 1.97, and it increased to approximately 20 immediately post-concussion.[34] At the time of injury, the GSC is the most sensitive (0.89) and specific (1.00) of the concussion assessments, and symptoms typically take about 5-7 days to return to normal values.[34] The biggest limitation of the GSC is that it is completely dependent on the student-athlete being honest about his or her symptoms, and with the issue of underreporting, hiding symptoms can put an individual at risk of returning to play too soon and sustaining a second injury.

Impaired postural control is a cardinal symptom following concussion.[2] The most commonly used postural control assessment in the multifaceted concussion battery is the Balance Error Scoring System, or BESS.[2] The BESS requires three different stances (double leg, single leg, tandem) on two different surfaces (firm, foam).[69] Student-athletes are asked to hold each position for 20 seconds with hands on hips and eyes closed, and the total number of errors is scored.[69] Each error is worth one point, and the six possible errors include removing the hands from the hips, opening the eyes, taking a step or falling, flexing the hip greater than 30 degrees, lifting the forefoot or heel and remaining out of position for longer than 5 seconds.[69] The average score of the BESS at baseline is approximately 12, and it increases to around 19-20 immediately following concussion.[34] It typically takes about 3-5 days for BESS scores to return to baseline value.[34] The sensitivity of the BESS is highest at time of injury, but even then it is only 0.34, which is one of its many limitations.[34] In addition to low sensitivity, the BESS is limited by poor reliability, practice effects and testing environment.[70–72]

In terms of cognitive testing, the Standard Assessment of Concussion (SAC) is the most commonly used assessment.[2] The SAC is a mental assessment that examines orientation, immediate and delayed memory, and concentration.[73] Traditional SAC scores fall between 26-27 and drop 3-4 points immediately post-concussion.[34,74] The sensitivity of the SAC is relatively high at time of injury (0.80), but it rapidly declines post-injury, and scores typically return to baseline in about 2 days.[34,74] For this reason, the consensus recommends that SAC should not be used for assessment of recovery.[2] Athletes who sustained LOC at time of injury have demonstrated to have significantly impaired SAC scores the first 15 minutes post-injury compared to those without LOC or amnesia, but by 48 hours post-concussion, significant differences were no longer seen.[74] It is important to note that cognitive and balance tests recover independently, but both recover before symptoms.[34]

A subset of the larger umbrella of cognitive testing is neuropsychological testing, which is commonly assessed by the Immediate Post-Concussion Assessment and Cognitive Testing (ImPACT). The ImPACT is a computerized test that measures verbal memory, visual memory, visual motor speed, reaction time and impulse control.[75] While ImPACT is currently considered to be the "gold standard" of neuropsychological testing, it is estimated that a false positive result occurs approximately 46% of the time.[76] Although alternative neuropsychological tests were utilized, the sensitivity of the full concussion assessment battery doubled (0.14 to 0.30) on Day 7 post-concussion when neuropsychological tests were incorporated, which lends support to their use throughout the recovery process.[34]

A more recent addition to the concussion assessment battery is the King-Devick (KD) test. Vision is commonly affected following concussion, and the KD test is a rapid number naming exam that requires saccadic eye movements, which have been shown to reflect impaired brain function.[77,78] The KD test requires the athlete to read a series of single-digit numbers, from left to right, as quickly as possible.[79–81] There are 3 sets of cards, for both paper and iPad, and the score is the time it takes to get through all of them.[79–81] The average baseline score in collegiate student-athletes is approximately 42 seconds, and any change in time from baseline is considered a meaningful change.[77] Combining the KD and SAC assessments identified 89% of concussions in a collegiate student-athlete population, and this jumped up to 100% when BESS was incorporated; however, this was in a small subset of student-athletes already suspected of having a concussion, and there were no controls.[77]

Cognitive and Physical Rest

Cognitive and physical rest following concussion is the "cornerstone" of concussion management, and an initial rest period is recommended in the acute post-concussion stage (24-48 hours); however, specific research on cognitive rest is limited.[2] The initial rest period is advised to include limited cognitive and physical activity through the restriction of school attendance, academic work and exercise.[2] The rationale behind a period of rest following concussion is to reduce symptoms and lower the risk of the aforementioned SIS, but total reliance on rest as a treatment following concussion has demonstrated to do more harm than good.[82,83,84] Compared to those who were given a mandatory rest period on the day of injury and the following day, collegiate student-athletes with no rest restrictions following concussion became asymptomatic approximately 1.3 days earlier, demonstrating that a day of prescribed physical and cognitive rest was not a successful treatment for reducing concussion recovery time.[85] Furthermore, a recommendation of 5 strict rest days, compared to the usual 1-2, in a pediatric population did not improve symptom, neurocognitive or balance recovery outcomes.[86] In terms of post-concussion activity level, collegiate student-athletes performed better on neurocognitive tasks when they were allowed to do school activity and light household activity (e.g. mowing the lawn) compared to those who were restricted from all activity and those who were allowed to return to full activity.[87] These results suggest that a light level of prescribed activity may be beneficial in speeding up the recovery process compared to strict rest.

The reason behind the failure of strict rest to improve recovery time following concussion is not fully known; however, multiple theories have been proposed. One possibility is that removing an individual from his or her activities of daily living, such as academic and team functions, may increase risk of depression.[82] The term "situational depression" has been coined to describe the emotional distress a pediatric patient might experience during restriction of school and other activites.[86] Along with depression, removing student-athletes from their daily routines and limiting social interaction can increase feelings of anxiety and isolation.[88] It is important to acknowledge that removing an individual from normal activities for a short period of time is unlikely to result in clinically diagnosed depression or anxiety; however, this strict rest period and change in environment could prolong concussion recovery and should be considered throughout the recovery process.[85]

Return to Exercise

Returning an athlete to full participation following a concussion is one of the most challenging questions medical professionals face today. Thankfully, it has been unanimously agreed upon that no athlete should return to play on the same day as a concussive injury.[2] An athlete's response to a physiological stressor, such as exercise, can provide valuable insight as to when the body has fully recovered from a concussion.[89] It is essential to gain an understanding of how exercise affects the current clinical assessments, and if exercise induces an adverse effect in an athlete's sports performance, the return to play protocols can be compromised.[90,91] It is currently recommended that athletes recovering from a concussion undergo a period of both physical and cognitive rest until all symptoms subside. Growing research demonstrates the value of exercise in brain repair due to its ability to enhance cognitive performance and restore the disrupted autonomic balance.[92–94]

Time and exercise intensity are two of the most important factors to consider when progressing an athlete back to full participation. As with the metabolic cascade, a majority of the post-concussion exercise models come from animals. Rats introduced to exercise within the week first week post concussion had a decrease in plasticity markers and increase in memory impairments, but an increase in BDNF and cognitive function when exercise was withheld for 14-21 days, suggesting that post-concussion exercise is only beneficial when administered at the right time.[92,93] Documenting the presence of neurological symptoms following a concussion is a vital component in the decision of when an athlete can return to full athletic participation.[95] If exercise negatively affects the cognitive function of an athlete, a neuropsychological test should not be administered until he or she has recovered.[96] When administered to healthy individuals, a VO2 max treadmill test resulted in an impairment of verbal memory, immediate memory, and delayed memo.[96] These results have important clinical implications because they demonstrate that maximal exercise can have an adverse effect and therefore, a neuropsychological test should not be administered to an athlete with a suspected concussion immediately after the injury.[95,96]

While high intensity exercise protocols, in research, have resulted in cognitive dysfunction, moderate-intensity exercise seems to produce a more positive result. Symptom evaluation following high intensity exercise tasks demonstrated an increase in the presence of symptoms when compared to moderate intensity exercise, even continuing through fifteen minutes of rest.[95] Additionally, moderate intensity exercise actually improved two of the three outcome measures of common motor performance tasks used in neurological assessments.[90] These results demonstrate that post-concussion symptoms during recovery can be influenced by exercise intensity, and clinicians need to take the intensity of the exercise protocol into consideration when rehabbing an athlete.

Concussion & Musculoskeletal Injury

There is increasing evidence of an association between concussion and subsequent lower extremity injury within the following year.[97–107] Within the first year after a concussive injury, collegiate athletes are 1.64-2.48 times more likely to suffer an acute lower extremity musculoskeletal injury in the year following concussion, compared to healthy controls who are not concussed.[98,100,102] The risk is similar for professional athletes (1.47-2.23 increased risk).[97,99,101,104,108] Approximately 61% of retired NFL players reported suffering a concussion during their NFL careers, and there was a dose-response relationship between concussion history and odds of reporting a musculoskeletal injury.[109] The players who reported one concussion had an 18-63% increased risk of musculoskeletal injury, two concussions was associated with a 15-126% increased risk and three or more had 73-165% higher odds of reporting musculoskeletal injury.[109] Additionally, European male soccer players were found to have a 2.2 times increased risk of injury in the year following concussion, as well as an elevated risk of injury in the year prior to concussion.[101]

These results raise the question of are these athletes just more injury prone, or is there something happening on the motor control level that is putting them at increased risk for injury following concussion. Postural and neural control deficits, similar to those seen following concussion, have demonstrated to increase the risk of noncontact lower extremity injuries in healthy individuals.[110] Therefore, it is possible that these athletes are suffering from lingering postural deficits up to a year following concussion, which is putting them at risk for subsequent musculoskeletal injury.

Concussion and Gait

As previously mentioned, postural control, as assessed by the BESS test, typically recovers in 3-5 days.[34] However, the BESS is a test of static postural control, and it has been suggested that more dynamic tasks are better at identifying postural deficits following concussion.[111] It is possible that the increased number of lower extremity injuries occur because there are still lingering postural deficits in the year following concussion that are not uncovered by traditional clinical assessments. Gait parameters can be utilized to determine level of neurological functioning.[112] Gait is an innate, or non-novel, dynamic task, which makes it a useful tool because gait parameters are not susceptible to the practice effects seen in some of the more novel tasks of the concussion assessment battery.[113] After the age of ten, changes in gait parameters (e.g. gait velocity, stride length) are minimal.[113] A voluntary destabilizing movement, such as gait, is derived from motor commands that arise in the cerebral cortex and travel down to the brainstem and spinal cord, with supraspinal control coming from multiple higher-level centers (basal ganglia, motor cortex, supplementary motor area, cerebellum)[114–116] The lower-level controller in the spinal cord is a network of interneurons referred to as central pattern generators (CPGs) that control rhythmic motor patterns.[115–119] While there is evidence that CPGs can generate rhythmic activity without inputs from higher-level supraspinal controllers,[115–119] they appear to also receive descending commands from the motor cortex and pyramidal tract to initiate the appropriate motor program to carry out the rhythmic movements necessary for locomotion.,[117,120] Unlike quiet stance, gait is less reliant on sensory feedback, as CPGs and supraspinal planning are predominantly responsible for the feedforward control.[121,122]

Concussions can lead to deficits in the ability to maintain gait stability.[123,124] Maintaining balance and limb coordination during sports requires a complex interaction of sensory input and motor output.[123] The combination of motor disabilities and cognitive impairments increase a concussed athlete's chances of experiencing postural instability and/or subsequent concussions.[124] Acutely post-concussion, there is evidence of impaired postural control, as indicated by slower gait velocity, reduced horizontal separation of the COP-center of mass (COM), and increased double support time have been observed both acutely post-concussion and up to 2 months following injury; therefore, these observations suggest the presence of a conservative gait strategy that persists beyond typical post-concussion clinical recovery.[111,124–134] In a healthy individual, gait velocity will typically fall somewhere between 1.4-1.6 m/s.[135] In the acute window following concussion, gait velocity has been observed to drop approximately 0.13 m/s.[111,123,124,136] When gait velocity returns to normal following a concussion varies across studies. Typically, a return to normal value is seen within 5-6 days post injury; however, there is evidence that gait velocity is still abnormal as far as 28 days post-concussion.[111,112,130,137] Buckley et al., noted that gait velocity had returned to normal in collegiate athletes by day 10 post-concussion; however, there was still evidence of a conservative gait strategy, independent of gait velocity, at day 10.[138]

Gait is not the only dynamic movement that should be addressed following concussion. Gait initiation is the transition from quiet stance to steady-state gait, and it requires the generation of propulsive forces while maintaining appropriate postural control during the motor task.[139,140] The supraspinal control of gait initiation is thought to originate from the supplementary motor area and motor cortex, based on evidence from animal and stroke studies.[121,141,142] Anticipatory postural adjustments (APAs) are likely responsible for the feedforward control to maintain postural control during the transition gait initiation to gait.[141] Transitional movements, such as gait initiation and gait termination, have demonstrated to be successful in identifying post-concussion postural control impairments.[126,140]

Access to full biomechanics and gait labs is limited; however, recent advances with inertial sensors and accelerometers have demonstrated post-concussion impairments in postural control and may improve clinical feasibility for postural control assessment.[143] The advancement of inertial sensors (accelerometers and gyroscopes) embedded in inertial measurement units (IMUs) has provided an alternative to expensive laboratory setups for gait evaluation.[144–147] Wearable IMUs have demonstrated success in evaluating postural sway and quantifying APAs during gait initiation in Parkinson’s disease[144,148–150], and mild traumatic brain injury[151], as well as gait in healthy collegiate athletes.[152] The APDM Opals, which are utilized in this study, have demonstrated to be feasible for use in a clinical setting, reliable when compared to laboratory force plates, and valid for use in both neurological and healthy populations.[144,149,150,153,154] Accelerometer-based measurements are providing the opportunity to transition post-concussion gait analysis, which has traditionally been performed with sophisticated lab setups, to more clinically-friendly settings, as they have been introduced as a tool for analyzing postural control both acutely post-concussion[134] and in individuals with a concussion history.[155]

Tandem Gait

Another test that can be used clinically to determine dynamic balance during locomotion is tandem gait (TG).[156–158] The third version of the Sport Concussion Assessment Tool, or SCAT3, has included TG as an alternative balance assessment to use in addition to or instead of the BESS; however the updated 5th version (SCAT5) has removed the standardized TG protocol and replaced it with a more subjective assessment.[159,160] A standard TG trial involves an individual walking, with an alternate heel to toe gait pattern, down a 3 meter line, performing a 180 degree turn at the other end and coming back to the starting line.[90,156] The normative value for a TG trial is approximately 11.2 seconds in healthy individuals, and it has been found to be highly reliable when administered by the same individual in the same session (ICC: 0.971) and in sessions a week apart (ICC:0.705), which demonstrates that it is a dependable measure of dynamic balance and should be utilized to examine neurological function following concussion.[156] When utilized as a screening tool for those with vestibular impairments, it was recommended that a tandem walking test not be used because it failed to identify differences between a normal healthy population and those with vestibular issue.[161] However, the TG task used in the vestibular study[161] only involved taking 10 TG steps forward, so it could be argued that the TG task performed following concussion is more challenging to the postural control system and is therefore better at identifying possible impairments.

Following a bout of high intensity exercise, a significant decline in both static and dynamic balance tasks can be seen.[91] When compared to a single leg static task, however, such as the stance utilized in the BESS, TG returned to baseline much quicker, suggesting that dynamic balance assessments are less affected by exercise than tasks more static in nature.[91] Clinicians should take this into consideration when examining individuals for a suspected concussion, both acutely and throughout the recovery process, particularly if the injury takes place during high-intensity exercise. Additionally, when examined as a predictor of prolonged recovery following concussion, a tandem walking task was not found to be a significant risk factor.[36]

Normative values of TG have been established in children[162], collegiate student-athletes[163], and professional athletes[164]; however, TG performance following concussion has been minimally explored.[165,166] Oldham et al., recently identified that TG performance was significantly worse acutely post-concussion, compared to controls, whereas the BESS performance slightly improved post-injury.[165] Further, TG presented with overall better psychometric properties than the BESS acutely post-concussion, which suggests that it may be better suited to identify impairments during that injury window.[165]

Concussions are a complex injury, and presentation and recovery differs from person to person. The number of concussions each year is alarmingly high, and it is imperative to protect athletes from the vast array of consequences that can result from concussive injuries. The multifaceted battery has demonstrated success with establishing appropriate tools for concussion assessment; however, future research is still warranted to improve upon the existing assessments, particularly in the realm of postural control. In addition, now that the relationship between concussion and subsequent lower extremity musculoskeletal injury has been identified, further research is needed to examine which variables put an individual at risk for injury following concussion.

Chapter 2

ASSESSMENT OF POST-CONCUSSION DYNAMIC POSTURAL CONTROL USING AN INSTRUMENTED DYNAMIC BATTERY

Introduction

Concussions are classified as a significant public health problem by both the NIH and the CDC, with an estimated 1.6-3.8 million concussions occurring annually, and an annual economic burden of approximately $22 billion.[167,168] In reality, 1.6-3.8 million is likely a low estimate since up to 80% of concussions go unreported.[167] A concussion poses significant health risks both acutely and chronically. Immediately following concussion, there is an elevated risk of suffering a recurrent concussion, as well as the risk of second impact syndrome, which is a rare, but potentially fatal condition.[32,169–174] Individuals with a concussion history are 3-5x more likely to suffer a future concussive injury compared to those with no history.[32,174] There are a number of long-term risks, such as later life depression, dementia, early onset Alzheimer's disease, and chronic traumatic encephalopathy, in those who have suffered a concussion;[41,53,61,62,175] therefore, concussions are a health risk to an individual across an entire lifespan.

Due to the heterogeneous nature of the injury, a multifaceted assessment battery, consisting of self-reported symptoms, cognitive, and postural control, is recommended to examine an individual throughout recovery and determine readiness for return to play.[29,176,177] The multifaceted battery is necessary because the different domains of concussion assessment recover independently.[29,178] While the total assessment battery is highly sensitive (0.89-0.96) for acute concussion diagnosis, the sensitivity significantly drops (0.30) within 7 days; therefore, it is an insufficient indicator of concussion recovery.[67,178] The most commonly used postural control assessment is the Balance Error Scoring System (BESS), which is a novel assessment that requires an individual maintain an upright stance while holding 3 different balance positions (double limb, single limb, tandem) on firm and foam surfaces.[29,179] The BESS has unacceptably low sensitivity (0.34) even acutely post-concussion, as well as low interrater (0.57) and intrarater (0.74) reliabilities, and high minimum detectable change scores (7.3-9.4 errors) that exceed normal post-concussion change.[178,180,181] Typical BESS scores return to baseline within 3-5 days, which is prior to symptom resolution and highlights the need for a more robust measure of post-concussion postural control assessment.[13,178] Further, the BESS examines postural control from a quiet or static stance domain, in which the goal is to maintain upright balance as opposed to coordinated movement; thus, it has been suggested that dynamic tasks are more suitable for identifying postural control deficits following concussion.[125] A dynamic motor activity of daily living, such as gait, is less likely to be susceptible to the limitations of a novel assessment like the BESS, potentially making it a more appropriate task for identifying post-concussion impairments in postural control.[51]

Gait is an innate, dynamic task that requires the activation of both the nervous and musculoskeletal systems and can be utilized to assess neurological functioning.[115,125,182] Healthy postural control requires a successful integration of the visual, vestibular, and somatosensory systems, as well as the motor and cognitive systems.[114] A voluntary destabilizing movement, such as gait, is derived from motor commands that arise in the cerebral cortex and travel down to the brainstem and spinal cord, with supraspinal control coming from multiple higher-level centers (basal ganglia, motor cortex, supplementary motor area, cerebellum)[114–116] The lower-level controller in the spinal cord is a network of interneurons referred to as central pattern generators (CPGs) that control rhythmic motor patterns.[115–119] While there is evidence that CPGs can generate rhythmic activity without inputs from higher-level supraspinal controllers,[115–119] they appear to also receive descending commands from the motor cortex and pyramidal tract to initiate the appropriate motor program to carry out the rhythmic movements necessary for locomotion,[117,120] and unlike quiet stance, gait is less reliant on sensory feedback, as CPGs and supraspinal planning are predominantly responsible for the feedforward control.[121,122]

Gait is not the only dynamic component of locomotion that should be evaluated. Based fMRI evidence, transitional movement paradigms, such as gait initiation (GI), are controlled by their own supraspinal regions and are likely more challenging to the dynamic postural control system, as they require a greater number of neurological resources.[183] Gait initiation is the transition from quiet stance to steady-state gait which requires the generation of propulsive forces while maintaining appropriate postural control during the motor task.[139,140] The neurologic control of GI on a supraspinal level is thought to originate from the supplementary motor area and motor cortex, based on evidence from animal and stroke studies.[121,141,142]

During a planned action, anticipatory postural adjustments (APAs) are likely responsible for the feedforward control to maintain postural control during the transition gait initiation to gait.[141] During GI, center of pressure (COP) displacement is divided into three phases: the APA phase (S1), the transitional phase (S2), and the locomotor phase (S3).[184,185] Alterations in the COP phases of GI have been observed following concussion,[126,140] suggesting that it is a transitional movement capable of elucidating postural control impairments in a concussed population.

Evidence of impaired postural control, as indicated by slower gait velocity, reduced horizontal separation of the COP-center of mass (COM), and increased double support time have been observed both acutely post-concussion and up to 2 months following injury, which suggests the presence of a conservative gait strategy that persists beyond typical post-concussion clinical recovery.[111,124–134] Alterations in post-concussion transitional gait movements have also been identified.[126,140] Gait initiation has demonstrated to be a sensitive indicator of balance dysfunction in individuals with neurological impairments,[183] including Parkinson’s disease, stroke, and the elderly.[184–187] Additionally, Buckley et al., noted postural deficits in the APA phase of GI acutely post-concussion, which suggests impairment in the planning of GI.[140] These COP alterations during GI reflect changes in APAs acutely following concussion[126]; therefore, it is important to examine planned GT beyond the acute time point to determine how long the postural control impairments persist. Although these postural control impairments have been observed to extend beyond clinical recovery, the full extent remains largely unknown; however, conservative gait strategies have been observed in individuals with a history of at least one concussion, which suggests that gait deficits could potentially persist chronically and serve as early indicators of long-term neurological impairment.[48–50]

While these overall postural control deficits have been observed during single-task gait, the impairments are particularly evident during dual-task.[133,188,189] Dual-task (DT) paradigms have been utilized to study the combination of attention and postural control, during which postural control and a cognitive task are combined with the each other.[190] A decline in the performance of either task is indicative of an interference between the two, due to a possible sharing of attentional resources, or a bottleneck approach, where the two tasks require the same underlying mechanism simultaneously.[191,192] Both motor and cognitive performance are impaired post-concussion[29,193], and the use of a DT paradigm allows one to simultaneously evaluate both domains. Dual-task gait has been successful in identifying postural control impairments acutely post-concussion, as well as up to 2 months following injury.[124,125,127,128,133,188,189,194] Further, the evaluation of gait stability during a DT assessment has also been suggested to be a sensitive indicator of long-term deficits in motor control.[48] Impairments in postural control during steady state gait have been clearly identified in a DT environment; however, DT GI following concussion has not been explored, which could potentially serve as a more robust indicator of post-concussion postural control recovery.

The altered movement strategies observed during gait tasks have been elucidated utilizing sophisticated, instrumented labs with full motion capture systems and force plates; thus, the technology is costly and largely unavailable in many clinical settings. The advancement of inertial sensors (accelerometers and gyroscopes) embedded in inertial measurement units (IMUs) has provided an alternative to expensive laboratory setups for gait evaluation.[144–147] The use of these wearable IMUs has been successful in evaluating postural sway and quantifying APAs during GI in Parkinson's disease[144,148–150], and mild traumatic brain injury[151], as well as gait in healthy collegiate athletes.[152] The APDM IMUs have demonstrated to be feasible for use in a clinical setting, reliable when compared to laboratory force plates, and valid for use in both neurological and healthy populations.[144,149,150,153,154] Accelerometer-based measurements have been introduced as a tool for analyzing postural control both acutely post-concussion[134] and in individuals with a concussion history[155], which has the potential to transition post-concussion gait analysis from labs to more portable, clinician-friendly settings.

The presence of dynamic postural control impairments, specifically a conservative gait strategy, during both gait related tasks, has been well established; however, the existing studies are cross-sectional in nature and lack pre-injury baseline data for a within-subject comparison. This investigation provided both a between and within-subject approach, as it not only compared post-concussion postural control outcomes to those of healthy controls, but also to each individual's own baseline data. Further, it remains unclear how these postural control impairments evolve across a traditional clinical post-concussion recovery timeline; therefore, the purpose of this aim was to identify post-concussion GI and gait deficits using an instrumented dynamic battery utilizing both single-task and dual-task challenges. We have proposed the use of a dynamic postural control battery that uses wearable accelerometers to identify post-concussion deficits in postural control potentially not detected by traditional clinical milestones and to examine the duration of these deficits across a typical concussion recovery timeline. We hypothesize that these gait measures will identify impaired postural control, both acutely post-concussion and at return to play.

Specific Aim 1: Description

To identify post-concussion gait initiation and gait deficits using an instrumented dynamic battery utilizing both single-task and dual-task challenges across the traditional recovery timeline.

H1. All gait measures will identify postural control impairments acutely post-concussion during both single-task and dual-task challenges. The single-task gait outcomes will stabilize by return to play; however, the dual-task outcomes will remain impaired. Gait initiation will identify postural control impairments during both single and dual-task challenges that will persist through return to play. The significance of Aim #1 will be the identification of gait deficits throughout post-concussion recovery, despite apparent clinical recovery.

Methods

Participants

All student-athletes and cheerleaders at the University of Delaware were recruited to participate in the baseline component of the study. Concussion participants were included in the study if they were diagnosed with a concussion within the study timeframe and had valid baseline data (i.e. the student-athlete completed the full gait protocol prior to the start of his or her competitive season). All concussions were identified by a certified athletic trainer and formally diagnosed by a physician, consistent with the 5th International Consensus Statement on Concussion in Sport.[29] Control participants were active, healthy non student-athletes with no history of concussion within the past 6 months. Concussion history included both diagnosed and undiagnosed concussions, which was determined from a health history questionnaire.

The exclusion criteria for both the concussion and control groups included any self-reported neurological disorder, current lower extremity orthopedic injury, and self-reported metabolic, vestibular, vision, or other disorders that would impair normal gait performance. Each participant provided oral and written informed consent in accordance with the university's Institutional Review Board (IRB).

	Concussion (n= 34)	Controls (n= 28)
Age (years)	20.6 ± 1.6	20.8 ± 1.5
Height (cm)	174.3 ± 11.0	171.3 ± 9.2
Mass (kg)	72.2 ± 12.4	74.2 ± 16.0
Concussion history (n)	38% (13/34) 0.5 ± 0.9 (range, 0-4)	21% (6/28) 0.3 ± 0.8 (range, 0-4)
Sex (M/F)	14/20	15/13

Table 1. There were no significant differences between the concussion and control groups at baseline for age (p= 0.72), height (p= 0.16), weight (p= 0.18), or concussion history (p=0.29).

Instrumentation

All participants were instrumented with three wearable triaxial accelerometers (Opal Sensor, APDM Inc., Portland, OR.)[195] (Figure 1) The APDM accelerometers have demonstrated to be feasible for use in a clinical setting, reliable when compared to laboratory force plates, and valid for use in both neurological and healthy populations.[144,149,150,153,154] Each accelerometer included a triaxial gyroscope and triaxial magnetometer, and the sampling was 128 Hz. There was an Opal on the dorsal surface of each foot, as well as at L5, and each accelerometer was secured with an adjustable, elastic band. (Figure 2)

Figure 1. APDM Opal IMU

Figure 2. Placement of the Opal IMUs

Procedures

The dynamic postural control battery consisted of GI and gait stepping characteristics. Each gait task was performed first in a single-task setting, followed by dual-task. The dynamic battery was performed across multiple concussion clinical milestones: baseline (prior to the student-athlete's competitive season), acute post-concussion (within 48 hours post-injury), asymptomatic (the day the student-athlete no longer reported symptoms), and return to play (the day the student-athlete was cleared to return to full sports participation). (Figure 3)

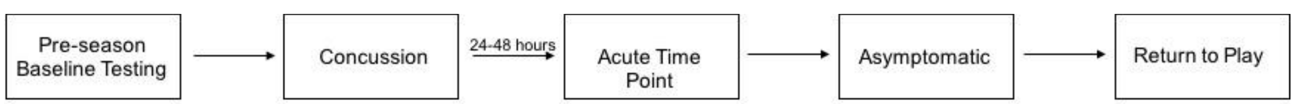

Figure 3. Timeline of the clinical concussion testing battery.

Gait

All participants began each trial standing behind a visible starting line and, in response to a verbal cue, walked down a 10-meter walkway at a self-selected pace, turned around a specified endpoint, and return to the original starting point. (Figure 4) During the dual-task condition, participants completed the same gait protocol while simultaneously answering a mini-mental style battery of questions (Appendix B). Each participant was instructed to begin walking when the first question was administered. There were no instructions given as to how to prioritize the cognitive versus motor task. Five trials of both single-task and dual-task gait were performed, along with 5 trials of quiet stance static balance.

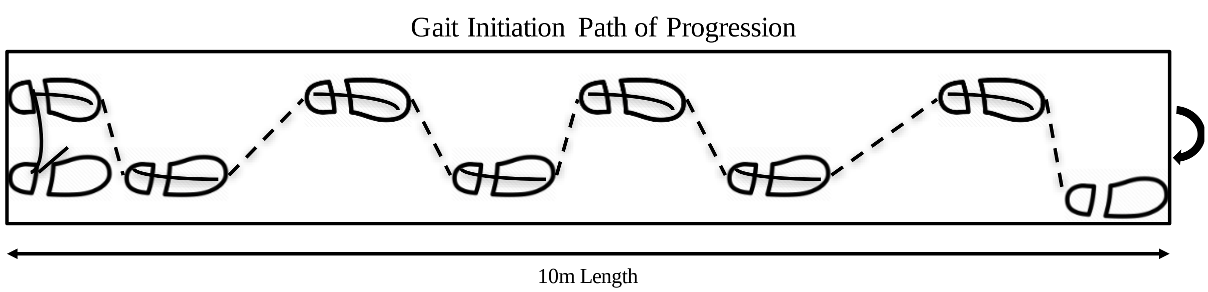

Figure 4. Path of progression

Gait Initiation

Gait initiation was measured as a component of the dynamic postural control battery. The first two steps the participant took were considered the GI component. Movement initiation (i.e. the onset of APAs) was based on the first measurable change from baseline and was detected by an automated threshold-based algorithm, with a threshold of twice the standard deviation of the acceleration signal during the initial period of each trial.[149] The APAs were considered completed when COP in both the forward and lateral directions returned to baseline values.[149] (Figure 5)

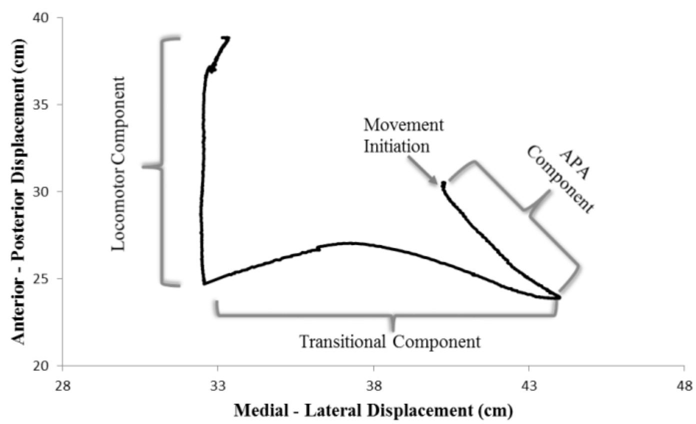

Figure 5. Exemplar figure of GI COP.

After the first two steps (one heel strike to the contralateral heel strike), the participant kept walking, turned around the specified turning point, and returned to the original starting line. (Figure 4) Each participant initiated gait with a self-selected limb, which could vary from trial to trial, in response to a verbal cue given by a member of the research team following an auditory signal from Mobility Lab. For the dual-task challenge, the participant was instructed to begin walking as soon as a member of the research team gave one of the specific tasks (i.e. said a word for the participant to spell). The dual-task protocol is listed below in the “Dual-Task Cognitive Battery” section.

Dual-Task Cognitive Battery

The cognitive questions consisted of 3 different forms: 1) reciting the months of the year in reverse order, 2) spelling a five-letter word backwards, and 3) serial subtraction by 6s or 7s from a randomly selected number.[133,166] (Appendix B) The individual was awarded a check mark for each correct month of the year he or she recited. If a month was skipped, that month was considered an incorrect answer. The five-letter word had to be spelled correctly backwards to receive a correct score. Any error in spelling was counted as incorrect. Similarly, each number subtracted correctly was correct; however, if the individual said an incorrect number, but later corrected the pattern, the subsequent answer would be counted as correct. For example, if the task was to subtract by 7s, and the individual said "100, 93, 87, 80…," 87 would be marked as incorrect, since it was only 6 less than 93, but 80 would be counted correct. There were no prioritization instructions given for the cognitive or motor task. There were 5 trials performed under the dual-task condition, and the order of cognitive tasks was randomized each time.

Data Analysis and Statistical Approach

This study utilized a within and between-subjects prospective longitudinal approach, during which post-concussion postural control parameters were compared at multiple clinical milestones throughout the concussion recovery process. All of the dependent variables of the instrumented dynamic battery were measured with the APDM Opals and analyzed within the Mobility Lab software,[196] and a detailed table outlining analysis of the variables can be found in the Appendix. (Appendix A)

There were four dependent variables included during gait: gait speed, cadence, stride length, and double support time. The gait speed (m/s), was reported as the distance divided by time.[196] The cadence was the number of steps taken per minute, which the Opals analyzed from the angular velocities recorded from the gyroscopes on the left and right feet.[144,196] The stride length was calculated from the distance between consecutive heel strikes on the same foot and was also analyzed by the Opals from the angular velocities recorded by the gyroscopes on the left and right feet.[144,196] Double support time was the percentage of the gait cycle during which both feet are in contact with the ground.[196]

The dependent variables analyzed during gait initiation included APA duration, first step duration, first step range of motion (ROM), forward peak APA acceleration, and lateral peak APA acceleration. The APA duration was recorded as the time from APA onset to the heel strike and was analyzed by an algorithm within Mobility Lab that utilized the 3D acceleration signals and the angular velocities from the left and right foot Opals to quantify first step characteristics.[144,149] The APA first step duration was the time-to-peak angular velocity from the end of the APA to the heel-strike and was analyzed by an algorithm within Mobility Lab that utilized the 3D acceleration signals and the angular velocities from the left and right foot Opals to quantify first step characteristics.[144,149] The APA first step ROM was the integrated angular velocity of the shank from the end of the APA to the heel strike and was analyzed by an algorithm within Mobility Lab that utilized the 3D acceleration signals and the angular velocities from the left and right foot Opals to quantify first step characteristics.[144,149] The forward peak APA acceleration was the forward trunk peak acceleration from baseline and was analyzed from an algorithm that used the 3D acceleration signals from the Opal worn on L5.[144,149] The lateral peak APA acceleration was the peak acceleration toward the stance foot from baseline and was analyzed from an algorithm that used the 3D acceleration signals from the Opal worn on L5.[144,149]

The dependent variables measured during turning included turn duration (seconds) and peak turning velocity (degrees/second). Turning was detected and assessed based on the gyroscropes within the lumbar Opal. A previously established mathematical model was utilized to determine the exact moment of the beginning and end of the turn.[196,197] The turning duration was defined as the duration of the 180 degree turn and was measured by the lumbar Opal.[196] The peak turning velocity was the 95% angular velocity of the trunk during the turning period, and it was measured by the lumbar Opal.[196]

The dependent variables analyzed during the DT conditions were cognitive accuracy (i.e. the percentage of correct answers out of the total possible answers), and the total number of correct answers.

Demographic data for the study participants were compared between groups using independent samples t-tests. The dependent variables of interest were compared utilizing a linear mixed-effects model. Any significant group x time interactions were followed up with post-hoc testing for fixed effects, which allowed for examination of between group differences. Statistical significance was set at alpha < 0.05, and all statistical models were performed with SPSS Statistics Version 25 (IBM Cop, Armonk, NY).

Results

There were 34 student-athletes eligible for inclusion in the concussion group, and 28 healthy controls for Aim 2. (Table 1) Within the control group, two participants were removed due to no longer meeting inclusion criteria during the testing sessions. The time between testing sessions can be seen in Table 2.

Time Points	Concussion	Controls
Injury to Acute	1.90 ± 0.40	1.92 ± 0.40
Acute to Asymptomatic	10.60 ± 13.00	19.90 ± 11.26
Asymptomatic to RTP	6.78 ± 7.18	7.82 ± 8.13

Table 2. Mean ± SD of the number of days between testing time points. There were no significant differences between groups for injury to acute (p= 0.50), or acute to asymptomatic (p= 0.62). There was a significant difference between groups for asymptomatic day to RTP (p=0.03).

Single-Task APA Characteristics

There were no significant group x time interactions for ST APA duration (F= 0.854, p= 0.466), forward peak APA acceleration (F= 0.343, p= 0.795), or lateral peak APA acceleration (F= 0.304, p= 0.822). Single-task APA duration had no significant group (F= 3.407, p= 0.067) or time (F= 0.773, p= 0.511) effects. Single-task forward peak APA acceleration had no significant group (F= 0.469, p= 0.494) or time (F=

1.051, p= 0.371) effects. Single-task lateral peak APA acceleration had no significant group (F= 2.207, p= 0.139) or time (F= 0.664, p= 0.575) effects. Raw data for ST APA characteristics can be found in Appendix C.

Dual-Task APA Characteristics

There were no significant group x time interactions for DT APA duration (F= 0.820, p= 0.484), forward peak APA acceleration (F= 0.570, p= 0.636), or lateral peak APA acceleration (F= 0.869, p= 0.458). Dual-task APA duration had no significant group (F= 0.135, p= 0.714) or time (F= 0.209, p= 0.890) effects. Dual-task forward peak APA acceleration had no significant group (F= 1.366, p= 0.244) or time (F= 1.669, p= 0.175) effects. Dual-task lateral peak APA did have a significant group effect (F= 4.469, p= 0.036) (Table 3), but no significant time (F= 0.456, p= 0.714) effect. Raw data for DT APA characteristics can be found in Appendix C.

			95% Confidence Interval		Mixed Model	
Group	**Mean**	**Standard Error**	**Lower Bound**	**Upper Bound**	**F**	***p***
Concussion	0.040	0.002	0.036	0.043	4.469	0.036
Controls	0.035	0.002	0.032	0.039		

Table 3. Estimates of significant group effect for DT lateral peak APA (m/s^2) during gait initiation.

Single-Task First Step Characteristics

There were no significant group x time interactions for ST first step duration (F= 0.209, p= 0.890) or first step range of motion (F= 0.688, p= 0.561). There were significant group (F= 12.480, p= 0.001) and time (F= 3.671, p= 0.013) effects for ST first step duration. (Table 4 A and B) Raw data for ST first step characteristics can be found in Appendix C.

A. Single-Task First Step Duration Group Effect

			95% Confidence Interval		Mixed Model	
Group	**Mean**	**Standard Error**	**Lower Bound**	**Upper Bound**	**F**	***p***
Concussion	0.486	0.004	0.477	0.494	12.480	0.001
Controls	0.464	0.004	0.455	0.472		

B. Single-Task First Step Duration Time Effect

			95% Confidence Interval		Mixed Model	
Time	**Mean**	**Standard Error**	**Lower Bound**	**Upper Bound**	**F**	***p***
Baseline	0.487	0.006	0.475	0.498	3.671	0.013
Acute	0.482	0.006	0.470	0.495		
Asymptomatic	0.466	0.007	0.453	0.480		
RTP	0.463	0.006	0.451	0.475		

Table 4. A: Significant group effect for ST first step duration (s). B: Significant time effect for ST first step duration (s). There was no difference from baseline to acute (p= 0.616). There was a significant difference between baseline and asymptomatic (p= 0.023), and baseline and RTP (p= 0.005).

There was a significant group effect (F= 11.283, p= 0.001), but not time effect (F= 0.382, p= 0.766) for ST first step ROM. (Table 5)

			95% Confidence Interval		Mixed Model	
Group	**Mean**	**Standard Error**	**Lower Bound**	**Upper Bound**	**F**	***p***
Concussion	26.44	0.73	25.00	27.88	11.283	0.001
Controls	23.01	0.72	21.59	24.42		

Table 5. Estimates of significant group effect for ST first step ROM (degrees) during GI.

Dual-Task First Step Characteristics

There were no significant group x time interactions for DT first step duration (F= 1.020, p= 0.385), or first step ROM (F= 0.488, p= 0.691). There were no significant group (F= 1.015, p= 0.315) or time (F= 1.988, p= 0.118) effects for DT first step duration. There were no significant group (F= 0.338, p= 0.562) or time (F= 0.815, p= 0.487) effects for DT first step ROM. Raw data for DT first step characteristics can be found in Appendix C.

Gait Speed

There was not a significant group x time interaction for ST gait speed (F= 0.880, p= 0.452). There was not a significant effect for group (F= 0.000, p= 0.991) or time (F= 1.296, p= 0.277) for ST gait speed.

There was a significant group x time interaction (F= 2.966, p= 0.033) for DT gait speed. (Figure 6) There was not a significant effect for group (F= 0.517, p= 0.473) or time (F= 1.654, p= 0.178) for DT gait speed. Raw gait speed data can be found in Appendix D.

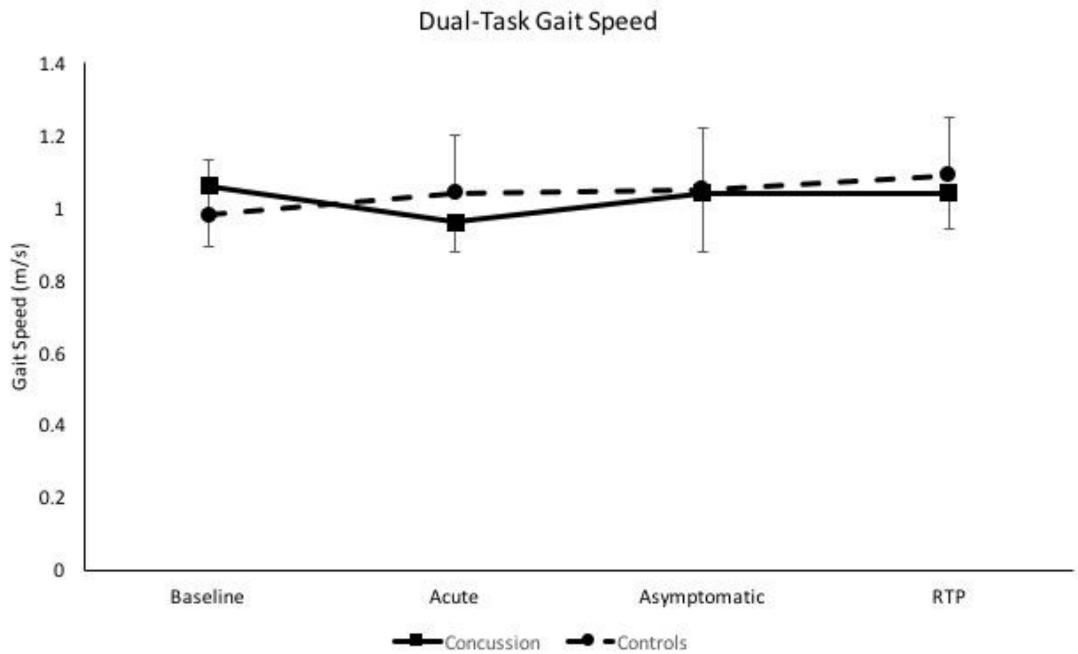

Figure 6. Interaction between the concussion and control groups for DT gait speed.

Double Support

There was not a significant group x time interaction for ST double support time (F= 0.208, p= 0.891). There was not a significant group effect (F= 1.774, p= 0.185) or time effect (F= 1.873, p= 0.136) for ST double support time.

There was not a significant group x time interaction for DT double support time (F= 1.706, p= 0.167). There was not a significant group effect (F= 2.171, p= 0.142) or time effect (F= 1.394, p= 0.246) for DT double support time. Raw data for double support time can be found in Appendix D.

Cadence

There was not a significant group x time interaction for ST cadence (F= 0.060, p= 0.981). There was not a significant group effect (F= 2.824, p= 0.094) or time effect (F= 2.620, p= 0.052) for ST cadence.

There was not a significant group x time interaction for DT cadence (F= 0.125, p= 0.945). There were significant group (F= 4.646, p= 0.032) and time (F= 2.836, p= 0.039) effects for DT cadence. (Table 6 A and B) Raw data for cadence can be found in Appendix D.

A. Dual-Task Cadence Group Effect

			95% Confidence Interval		Mixed Model	
Group	**Mean**	**Standard Error**	**Lower Bound**	**Upper Bound**	**F**	***p***
Concussion	106.4	3.1	92.5	120.2	4.646	0.032
Controls	109.8	3.1	98.1	121.4		

B. Dual-Task Cadence Time Effect

			95% Confidence Interval		Mixed Model	
Time	**Mean**	**Standard Error**	**Lower Bound**	**Upper Bound**	**F**	***p***
Baseline	104.7	3.2	90.9	118.4	2.836	0.039
Acute	107.9	3.3	93.5	122.4		
Asymptomatic	109.2	3.3	93.4	125.0		
RTP	110.4	3.3	98.0	122.9		

Table 6. A. Significant group effect for DT cadence (steps/min). B. Significant time effect for DT cadence (steps/min). There was no difference from baseline to acute (p= 0.133). There was a significant difference between baseline and asymptomatic (p= 0.040), and baseline and RTP (p= 0.007).

Stride Length

There was not a significant group x time interaction for ST stride length (F= 1.386, p= 0.248). There was not a significant group effect (F= 0.288, p= 0.592) or time effect (F= 1.917, p= 0.128) for ST stride length.

There was a significant group x time interaction (F= 2.816, p= 0.040) for DT stride length. (Figure 7) There was not a significant group effect (F= 0.004, p= 0.949) or time effect (F= 1.015, p= 0.387) for DT stride length. Raw data for stride length can be found in Appendix D.

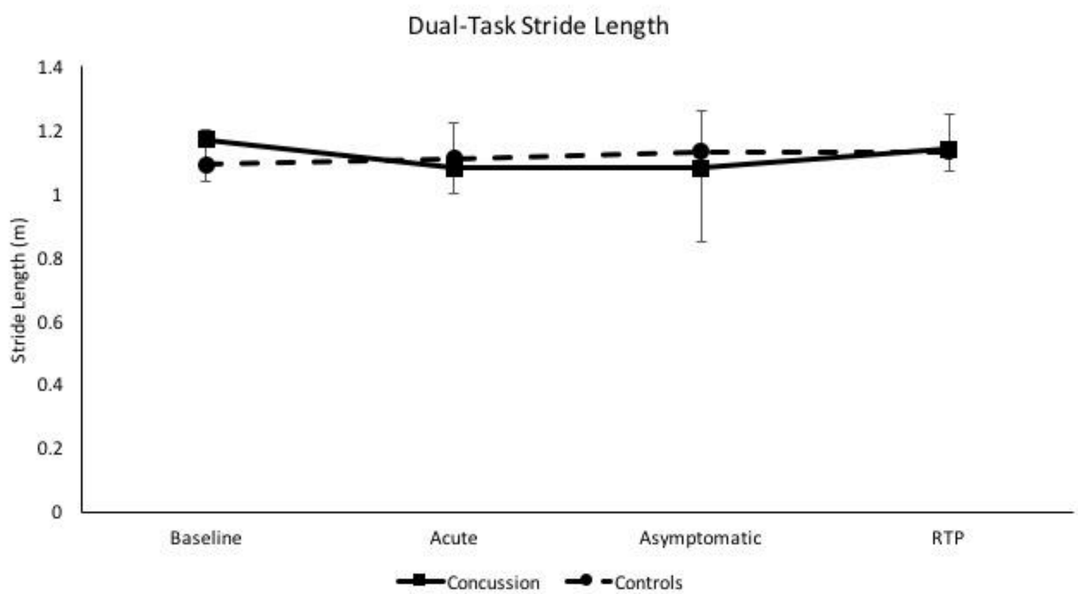

Figure 7. Interaction between the concussion and control groups for DT stride length.

Single-Task Turning

There were no significant group x time interactions for ST turn duration (F= 0.429, p= 0.733) or turn velocity (F= 0.645, p= 0.587). There was a significant time effect (F= 4.616, p= 0.004) (Table 7) for ST turn duration, but no significant group effect (F= 3.059, p= 0.082).

			95% Confidence Interval		Mixed Model	
Time	**Mean**	**Standard Error**	**Lower Bound**	**Upper Bound**	**F**	***p***
Baseline	2.39	0.24	1.93	2.85	4.616	0.004
Acute	2.24	0.24	1.78	2.70		
Asymptomatic	2.14	0.24	1.67	2.60		
RTP	2.20	0.24	1.74	2.67		

Table 7. Estimates of significant time effect for ST turn duration (s). There was a 0.15 second difference between baseline and acute (p= 0.039), a 0.25 second difference between baseline and asymptomatic (p< 0.001), and a 0.18 second difference between baseline and RTP (p= 0.009).

There was a significant time effect (F= 3.861, p= 0.010) for ST turn velocity, but no significant group effect (F= 0.757, p= 0.385). (Table 8) Raw data for turning can be found in Appendix E.

			95% Confidence Interval		Mixed Model	
Time	**Mean**	**Standard Error**	**Lower Bound**	**Upper Bound**	**F**	***p***
Baseline	181.6	48.3	103.8	259.4	3.861	0.010
Acute	189.3	48.3	50.6	328.0		
Asymptomatic	209.3	48.4	74.0	344.5		
RTP	200.1	48.3	47.5	352.7		

Table 8. Estimates of significant time fixed effect for single-task turn velocity (degrees/s). There was a 7.7 second difference between baseline and acute (p= 0.372). There was a 27.7 second difference between baseline and asymptomatic (p= 0.002). There was an 18.5 second difference between baseline and RTP (p= 0.028).

Dual-Task Turning

There were no significant group x time interactions for DT turn duration (F= 0.777, p= 0.508) or turn velocity (F= 0.562, p= 0.641).

There was a significant group effect (F= 6.267, p= 0.013), but not time effect (F= 1.792, p= 0.150) for DT turn duration. (Table 9)

			95% Confidence Interval		Mixed Model	
Group	**Mean**	**Standard Error**	**Lower Bound**	**Upper Bound**	**F**	***p***
Concussion	2.41	0.15	1.75	3.06	6.267	0.013
Controls	2.26	0.15	1.51	3.02		

Table 9. Estimates of significant group effect for DT turn duration (s).

There were significant effects for both group (F= 5.009, p= 0.026) and time (F= 2.901, p= 0.036) for DT turn velocity. (Table 10 A and B) Raw data for turning can be found in Appendix E.

A. Dual-task Turn Velocity Group Effect

			95% Confidence Interval		Mixed Model	
Group	**Mean**	**Standard Error**	**Lower Bound**	**Upper Bound**	**F**	***p***
Concussion	172.9	4.8	163.4	182.5	5.009	0.026
Controls	188.4	4.9	178.7	198.1		

B. Dual-task Turn Velocity Time Effect

			95% Confidence Interval		Mixed Model	
Time	**Mean**	**Standard Error**	**Lower Bound**	**Upper Bound**	**F**	***p***
Baseline	167.0	6.3	154.6	179.3	2.901	0.036
Acute	175.7	7.2	161.5	189.9		
Asymptomatic	190.3	7.3	175.9	204.7		
RTP	189.7	6.8	176.3	203.1		

Table 10. A. Significant group effect for DT turn velocity (degrees/s). B. Significant time effect for DT turn velocity (degrees/s). There was no difference from baseline to acute (p= 0.364). There was a significant difference between baseline and asymptomatic (p= 0.016), and baseline and RTP (p= 0.015).

Cognitive Variables

There were no significant group x time interactions for total number correct (F= 1.086, p= 0.356) or cognitive accuracy (F= 1.605, p= 0.189). Raw data for the cognitive tables is in Table 11.

		Concussion		Controls	
		n	**Mean ± SD**	***n***	**Mean ± SD**
Total Correct	**Baseline**	34	37.29 ± 17.05	28	29.82 ± 8.14
	Acute	20	35.35 ± 18.16	25	30.12 ± 7.54
	Asymptomatic	25	38.28 ± 20.99	19	29.16 ± 7.14
	RTP	25	46.52 ± 21.79	25	31.00 ± 5.36
Cognitive Accuracy	**Baseline**	34	89.46 ± 11.29%	28	95.40 ± 6.34%
	Acute	20	96.21 ± 6.40%	25	95.71 ± 6.26%
	Asymptomatic	25	92.50 ± 10.01%	19	96.26 ± 3.92%
	RTP	25	95.11 ± 6.48%	25	98.63 ± 1.96%

Table 11. Mean ± SD of total number of correct dual-task answers during TG in the concussion and control groups across the four time points. The "*n*" columns include the number of participants for both conditions at each time point.

There was a significant group effect (F= 5.009, p= 0.026) for total number of correct answers. (Table 12)

			95% Confidence Interval		Interaction	
Group	**Mean**	**Standard Error**	**Lower Bound**	**Upper Bound**	**F**	***p***
Concussion	39.36	12.02	-5.35	182.5	5.009	<0.001
Controls	30.03	12.03	178.7	198.1		

Table 12. Significant group effect for total number of correct answers.

There were significant group (F= 8.807, p= 0.003) and time (F= 3.725, p= 0.012) effects for cognitive accuracy. (Tables 13 A and B) Raw data for the cognitive variables can be found in Table 11.

13A. Cognitive Accuracy Group Effect

			95% Confidence Interval		Interaction	
Group	**Mean**	**Standard Error**	**Lower Bound**	**Upper Bound**	**F**	***p***
Concussion	93.32	3.28	70.60	116.05	8.807	0.003
Controls	96.50	3.29	77.39	115.61		

13B. Cognitive Accuracy Time Effect

			95% Confidence Interval		Interaction	
Time	**Mean**	**Standard Error**	**Lower Bound**	**Upper Bound**	**F**	***p***
Baseline	92.4	3.3	82.5	102.4	3.725	0.012
Acute	96.0	3.4	84.3	107.7		
Asymptomatic	94.4	3.4	84.1	104.7		
RTP	96.9	3.4	77.1	116.6		

Table 13. A. Significant group effect for cognitive accuracy (%). B. Significant time effect for cognitive accuracy (%). There was a significant difference from baseline to acute (p= 0.018). There was not a significant difference between baseline and asymptomatic (p= 0.191). There was a significant difference between baseline and RTP (p= 0.002).

Discussion

The effect of concussion on dynamic postural control has become an increasingly popular area of research, and the presence of a conservative gait strategy following concussion has been identified in numerous post-concussion populations.[111,114–116,124–134,198] This investigation was the first to utilize a within-subject approach with baseline data to examine a single-task and dual-task instrumented dynamic postural control battery across the clinical concussion recovery timeline. The primary finding of this study was a lack of significant single-task gait changes from baseline through RTP. However, more challenging tasks such as dual task gait, gait initiation, and turning did identify group differences, likely because these present greater neurological challenges. Thus, both researchers and clinicians can utilize dual-task gait movements following concussion to identify postural control deficits that may not appear during single-task challenges.

In the last decade, increasing evidence has shown that individuals utilize a conservative gait strategy following concussion.[111,114–116,124–134,198] Neurophysiological control of gait arises in the cerebral cortex and is supraspinally controlled from the multiple higher-level centers consisting of the basal ganglia, motor cortex, supplementary motor area, and cerebellum.[114–116] There is evidence that all of these neural centers are potentially affected by a concussive injury; thus, it is not surprising that impairments would arise post-concussion.[199–202] We did not observe any significant interactions or main effects for single-task gait speed, stride length, cadence, or double support time, which were the specific variables chosen due to having a history of successfully identifying post-concussion changes.[50,133,188] (Table 1) While evidence of a conservative gait strategy during single-task was not observed herein, our results compliment an existing body of literature that observed no change in gait speed, stride length, and cadence within the first 10 days following concussion.[111,124,127,131,133,155,188,203–206] Further, our results were similar to those reported by Howell et al., who utilized the same outcome measures from the APDM Opals to evaluate male and female adolescents following concussion.[207] This study is the first to examine these variables using a within-subject approach versus baseline, which is a potential reason for not seeing significant differences. It is possible that single-task gait is too automated to identify impairments in dynamic postural control when making the comparison of within-subject to healthy baseline, which is a more appropriate measure than a cross-sectional approach. Further, the conservative gait strategy that has been observed was done utilizing sophisticated motion capture systems with outcome measures related to center of mass acceleration; therefore, it is possible that those environments are better suit at identifying subtle single-task impairments.

Gait initiation has successfully identified postural control impairments in individuals with a variety of neurological disorders, and recently, in an acutely concussed population.[140,144,149,186] Herein, we utilized the APDM Opal wearable IMUs and Mobility Lab software, which have demonstrated to be valid and reliable in quantifying gait parameters, including those of the APA and locomotor phases of gait initiation; however, we did not observe any significant interactions in our APA variables during either single or dual-task conditions.[144,149,150,154,208,209] (Appendix C) These results differ from the recent literature demonstrating significant deficits in the APA phase of gait initiation following concussion.[140,210] The APA component of GI is thought to be controlled by the supplementary motor area (SMA),[141,142] which has demonstrated adverse effects following concussion;[199] however, we did not observe any indication of GI impairment in this population. As GI is a challenging task that encompasses motor planning, the lack of APA impairments would suggest adequate planning occurred during both ST and DT conditions. The lone difference observed among our APA variables was a significant group effect during DT lateral peak APA (peak acceleration toward the stance foot), whereby the concussion group had an overall 0.005g increase in lateral peak APA. (Table 3) Although slight, the increase in lateral peak APA was a surprising finding, and it could be attributed to compensatory strategy, as lateral displacement loads the limb and generates separation of the COP-COM. Mancini et al., observed a significantly smaller peak lateral APA acceleration in those with mild to moderate Parkinson's disease, compared to healthy older adults.[144,149,186,202] Despite the general absence of significant differences herein, our APA measures for both the concussion and control groups were similar to those previously established in healthy controls; thus, there did not appear to be differences between the populations in the planning and execution of GI.[144,149]

Similarly, there were no significant interactions for the first step variables in the locomotor phase of gait initiation. The first step measures utilized in this study were consistent with first step length and first step velocity, which have been utilized in prior post-concussion and Parkinson's disease gait initiation studies.[140,144,149] We observed significant group effects for ST first step duration and first step range of motion, whereby the concussion group had a longer duration (0.022 sec) and larger range of motion (3.4 degrees) thus suggesting longer but slower steps. (Tables 4A and 5) Therefore, it would appear that there was GI was planned successfully in the concussion group, but executed differently than the controls. Unlike the APA component, the GI locomotor component is primary regulated by motor cortex output,[141,142] so it is possible that motor cortex activity was influenced by the injury, resulting in altered initial step characteristics. Our first step duration and first step range of motion were fairly similar in both groups to what was previously reported in healthy controls, but more closely resembled the first step characteristics of those tested with mild Parkinson's disease.[144] Overall, these results elucidate alterations in the locomotor, as opposed to preparatory, phase of GI.

Significant interactions were present for DT gait speed and stride length, whereby the concussion group decreased speed and stride length acutely following concussion compared to controls at the same time point. (Figure 6 and 7) Similar results have been observed across multiple populations in the 10 days following concussion suggesting DT protocols may be better situated than ST to identify post-concussion postural control deficits.[124,125,127,131,134,203,205,206] A significant group effect was observed, where the concussion group had an overall slower cadence (↓3.39 steps/min) than controls. (Table 6A) As gait speed is a product of cadence and stride length, it was not surprising to see a slower cadence with the reduced gait speed in the concussion group. Increased activity in prefrontal areas has been observed in young adults during dual-task walking, and it has been suggested that the prefrontal cortex may be impaired acutely post-concussion, which could potentially be a factor in the slower gait parameters.[211–215] Appropriate activation in the prefrontal cortex is critical for working memory tasks, and fMRI evidence has demonstrated that concussed athletes required greater neural resources to achieve the same outcome in a dual-task challenge, thus requiring compensation.[216] We observed significant differences in our cognitive variables, as the total number of correct answers given during DT decreased (↓1.94), but the cognitive accuracy increased (↑6.75%); thus, individuals were providing fewer answers but getting more of them correct acutely post-concussion. (Tables 12 and 13) It appears the concussion participant's prioritized cognitive accuracy, so they reduced both gait and cognitive speed to prioritize cognitive accuracy. However, even though the accuracy increased, the number of answers given decreased, so it may still be considered a deterioration of the cognitive task. This could be a suggestive of the bottleneck theory, as both the motor and cognitive components of gait deteriorated.[192,217] Conversely, the control group's cognitive performance remained relatively consistent from baseline to acute for both total number correct (↑0.30) and cognitive accuracy (↑0.31%). (Tables 12 and 13) Concussed individuals may have a different task-related response than controls, which is considered to be a recruitment of other brain regions to compensate for the deficits in the prefrontal cortex following injury.[216] This weakened response is likely the reason for the differences in cognitive performance between the concussion and control groups further supporting the utilization of dual task challenges to assess neurological recovery following a concussion.

Turning is a necessary component of gait that requires a coordinated reorientation of the body; however, the turning aspect of post-concussion gait has been minimally explored compared to other gait components.[218,219] Herein, there were no significant group and time interactions for ST turn duration or turn velocity; however, significant time effects were observed for both. (Tables 7 and 8) There was a longer turn duration (ST: 2.39 sec, DT: 2.41 sec) and slower turn velocity (ST: 181.6 degrees/sec, DT: 167.0 degrees/sec) at baseline, with significant improvements across the four testing points. These results could be attributed to a general improvement in performance, which we also observed in single-task stepping characteristics. During DT turning conditions, a significant group effect demonstrated that the concussion group had an overall longer turn duration (0.15 sec) and lower turn velocity (15.5 degrees/sec) compared to controls. (Table 9) It has been suggested that turning movements are more susceptible to functional impairments than walking in a straight line, as it requires more coupling between posture and gait and different patterns in locomotion from the frontal lobe.[220] The aforementioned role of the prefrontal cortex during DT challenges, as well as the potential impairment of that brain region following concussion could explain the slower turns in the concussion group during DT gait. As this challenging aspect of postural control has received limited attention in the post-concussion population, future studies should further investigate the determinants of turning and incorporate both cognitive tasks (e.g., go/no-go) and planned vs unanticipated turning task challenges.

This investigation examined ST and DT gait in a collegiate athlete population; thus, extrapolations to other populations should be cautiously considered. Future research should utilize a within-subject approach in younger athlete populations to examine possible differences. As we were unable to predict when and where a concussion would occur, the testing environment for the concussion group was not consistent across all testing sessions, which could have potentially influenced gait characteristics, but this is common in concussion management clinical practice. All testing environments, however, were in a quiet, uninterrupted location. The controls could be more easily scheduled and were all tested in the same environment. Missing data across all four time points in the concussion group was another limitation of this investigation; however, it does provide a realistic view of clinical testing within a collegiate athlete population, as there are a number of factors that can result in missed follow-up sessions. We utilized wearable IMUs to evaluate our gait parameters, which are costly and not feasible for use across all clinical settings; however, they are more economically and clinically feasible than full motion capture laboratories. Regardless, future research should investigate more clinician-friendly postural control assessments (i.e. tandem gait) that can be utilized across all athletic environments.

This investigation did not identify the presence of an overall conservative gait strategy during instrumented ST gait across clinical concussion recovery. There were significant differences during more complex gait tasks, such as gait initiation initial step and turning, as well as significant cognitive differences during dual-task, which could be evidence of a compensatory strategy. While the lack of significant differences in ST gait, particularly acutely, was surprising, our results suggest that more challenging gait movements may be better suited for identifying impairments in dynamic postural control following concussion.

Chapter 3

EFFICACY OF TANDEM GAIT AS A POST-CONCUSSION POSTURAL CONTROL ASSESSMENT

Introduction

Impaired postural control is a common occurrence following concussion, and a gait/balance evaluation is recommended as part of a multifaceted approach to concussion assessment.[29,51] The old, but still widely used, Sport Concussion Assessment Tool-3 (SCAT-3) specifically recommends either tandem gait (TG) and/or the modified Balance Error Scoring System (mBESS) to assess post-concussion balance.[221] The recently released Sport Concussion Assessment Tool-5 (SCAT-5) still recommends the mBESS as the primary balance assessment; however, the previous SCAT-3 TG protocol of 4 timed trials has been replaced with the examiner's subjective evaluation of whether or not an individual can perform TG normally as part of the neurological screen of the SCAT-5.[160] While both the SCAT-3 and SCAT-5 include the mBESS as the recommended post-concussion balance assessment,[160,221] there is substantially less literature on it compared to the regular Balance Error Scoring System (BESS).

Recent studies have identified the sensitivity of the mBESS acutely post-concussion; however, the results are conflicting, with acute sensitivity values ranging from poor to moderate (0.47-0.71).[165,222] Poor sensitivity is also one of the multiple limitations of the BESS, with acute sensitivity values ranging from 0.34-0.45.[13,165,178] Further, the BESS has poor psychometric properties, with low interrater (0.57) and intrarater (0.74) reliabilities and high minimal detectable change (MDC) scores (7.3-9.4 errors) that exceed the normal post-concussion BESS change of 3-6 errors.[180,181] The BESS is also susceptible to a significant practice effect and is negatively influenced by the testing environment, ankle instability, and exertional fatigue, demonstrating that BESS performance is likely influenced by many factors other than concussion.[71,223–226] Thus, the results of the utilization of BESS as a diagnostic tool should be cautiously interpreted.

Tandem gait has not been investigated to the same degree as the BESS or mBESS in the concussion literature. The mBESS and BESS assess balance in a quiet stance environment, but it has been suggested that dynamic tasks are more suitable for identifying postural control impairments following concussion;[125] further, sophisticated gait measurements are costly and require extensive training, making them an unsuitable option across the majority of clinical settings; therefore, TG represents an alternative, clinically feasible method to evaluate postural control following concussion. A task originally developed to assess balance in individuals with cerebellar ataxia, TG is a clinically feasible and highly reliable (ICC: 0.97) method that evaluates dynamic balance, speed, and coordination.[156,227–229] The cerebellum, considered the “regulator of motor output,” receives and processes afferent information from multiple sensory systems, via the spinocerebellar pathway, and signals to the motor cortex and other control centers to carry out specific motions.[114,230] These signals are sent to the brainstem and relayed to the spinal cord via the vestibulo, rubro, and reticulospinal pathways, which in turn act directly on motor neurons to fine-tune movements to the specific need of the task, thus playing a key role in the regulation of balance and posture during coordinated movements.[114,230] The nature of the heel-to-toe pattern of TG makes it a highly coordinated movement; thus, it is a likely task to demonstrate impairments following concussion.[114,165,231,232]

Normative values of TG have been established in children[162], collegiate student-athletes[163], and professional athletes[164]; however, the effect of concussion on TG is largely underexplored. Oldham and colleagues recently examined TG performance acutely post-concussion, compared to each concussed athletes' own premorbid baseline, as well as a group of healthy controls, and demonstrated a significant and meaningful worsening (slower time) in TG following concussion compared to the healthy controls.[165] Further, when compared to mBESS and BESS, TG presented with better overall psychometric properties, including higher sensitivity (AUC(TG)= 0.704 compared to AUC(BESS)= 0.508 and AUC(mBESS)=0.535, respectively).[165] Another recent cross-sectional investigation identified worse TG performance (16.4 seconds vs 10.1 seconds) in a concussion group compared to controls, particularly in the dual-task setting.[166] Dual-task TG has also demonstrated to be associated with gait speed, which is one of several gait parameters that has demonstrated to be a useful marker following concussion;[233] therefore, TG may serve as an additional tool that clinicians can utilize in the assessment of post-concussion postural control.

Instrumented assessments utilizing transitional and steady state gait paradigms have been successful in identifying postural control impairments following concussion;[111,124–134] however, much of the post-concussion postural control literature has identified deficits through the use of sophisticated motion capture and force plate systems. Unfortunately, these instrumented measures are cost prohibitive and are not clinically feasible in the majority of clinical testing settings. While wearable accelerometers are an advancement over laboratory approaches, they are not yet economically feasible (~$17,000) for many sports medicine settings. The success of a TG task could allow for a translational approach from the laboratory to the sideline, due to its applicability in all post-concussion testing environments, minimal time and training, and low cost.

While TG has recently been explored acutely post-concussion,[165,166] the change of TG performance across the concussion recovery timeline is currently unknown. Other instrumented dynamic gait tasks have elucidated impairments up to 2 months after concussion, which is beyond typical clinical recovery of the BESS (3-5 days) to return to baseline.[13,188,189,194] These lingering deficits are particularly evident during DT gait, suggesting that including a simultaneous cognitive task with a motor task increases the sensitivity of the task to detect post-concussion postural control impairments. Howell et al., examined ST and DT TG across a 2-month time point following concussion and observed a longer duration of deficits in DT TG performance of the concussion group compared to controls.[166] The mean time to complete DT TG was significantly longer in the concussion group than controls at 72 hours, 1 week, and 2 weeks post-injury, which further suggests that TG impairments may persist beyond typical recovery of the most commonly used clinical tests.[166] Similarly, an examination of the best TG completion time revealed slower times in the concussion group versus controls at 72 hours and 1 week.[166] However, the Howell study utilized a cross-sectional approach, lacking pre-injury baseline data for the concussion participants, and utilized a sample size of only ten concussion and seven controls;[166] therefore, this investigation will provide a more robust examination of post-concussion TG performance, with the inclusion of pre-morbid data and a larger sample size.

The previously recommended SCAT-3 protocol instructed that four trials of TG be performed, with the best of the four times being recorded as the true TG time.[221] Early work by Schneiders et al., utilized three trials of TG and recorded the mean time of completion as the dependent variable.[90,91] The mean and best TG times have been included in the concussion literature, both as normative[163] and post-injury[166] data; therefore, both variables have been included in this investigation in order to provide the most true comparison between our study and previously published literature.

The presence of acute postural control deficits has been observed in both gait and TG following concussion, and lingering deficits have been observed in standard gait tasks; however, the effect of concussion on TG throughout the concussion recovery timeline is unexplored. Therefore, the purpose of this aim was the examine both ST and DT TG performance at clinical milestones across the post-concussion timeline. We hypothesize that TG will be a sensitive assessment acutely post-concussion and will stabilize by return to play.

Specific Aim 2: Description

To determine the efficacy of the clinically-feasible single-task and dual-task tandem gait task as a post-concussion postural control assessment.

H1. Single-task and dual-task TG will remain impaired through the asymptomatic day. Single-task TG will stabilize by return to play, but dual-task TG will continue to be impaired at return to play.

H2. Tandem gait will be a sensitive assessment for identifying postural control impairments following concussion. The success of the tandem gait task will translate post-concussion postural control assessment from the lab to clinical settings.

Methods

Participants

There were 65 participants in the concussion group, and 30 healthy individuals in the control group. (Table 14) All student-athletes and cheerleaders at the University of Delaware were recruited to participate in the baseline component of the study. Concussion participants were included in the study if they were diagnosed with a concussion within the study timeframe and had valid baseline data. All concussions were diagnosed by a certified athletic trainer and confirmed by a physician. Control participants were active, healthy individuals with no history of concussion within the past 6 months. Concussion history included both diagnosed and undiagnosed concussions, which was determined from a health history questionnaire.[106] The exclusion criteria for both the concussion and control groups included any self-reported neurological disorder, current lower extremity orthopedic injury, and self-reported metabolic, vestibular, vision, or other disorders that would impair normal gait performance. Each participant provided oral and written informed consent in accordance with the university's Institutional Review Board (IRB).

	Concussion (n= 65)	Controls (n= 28)
Age (years)	20.4 ± 1.5	20.8 ± 1.5
Height (cm)	175.1 ± 11.6	171.3 ± 9.2
Mass (kg)	75.4 ± 18.2	74.2 ± 16.0
Concussion history (n)	43% (28/65) 0.6 ± 0.8 (range, 0-4)	21% (6/28) 0.3 ± 0.8 (range, 0-4)
Sex (M/F)	26/39	15/13

Table 14. Participant demographics. There were no significant differences between the concussion and control groups at baseline for age (*p*=0.51), height (*p*=0.15), weight (*p*=0.17), or concussion history (p=0.61).

Instrumentation

The 3-m tape line utilized during the task was created from standard athletic tape (Johnson & Johnson, New Brunswick, NJ). All trials were timed using a hand-held stopwatch (Champion Sports, Marlboro, NJ).

Procedures

All participants began standing behind a starting line and, on a verbal cue, walked forward as quickly and accurately as possible along a 38mm wide, 3-meter long line with an alternate heel-to-toe gait. Each participant was instructed to touch the heel and toe on each step, consistent with SCAT-3 guidelines, which were in effect when the study began. (Figure 8) Once the participant crossed the opposite end of the line, he or she was instructed to complete a 180-degree turn and return to the starting line with the same heel-to-toe gait pattern. The time was stopped once the participant's full foot was across the starting line. To be considered a successful trial, participants could not step off the line or have separation between the heel and the toe. Any unsuccessful trials were repeated; however, this was a rare occurrence, as the majority of trials were successful.

Figure 8. Tandem gait.

A total of 4 trials were completed, for both ST and DT, and the best time out of the 4 trials was recorded. The mean of the 4 times was also calculated. The ST trials were to be completed in <14 seconds in healthy individuals, and there was no time cap for concussed individuals. There was no time cap for DT TG.

Dual-Task Cognitive Battery

The cognitive questions consisted of 3 different forms: 1) reciting the months of the year in reverse order, 2) spelling a five-letter word backwards, and 3) serial subtraction by 6s or 7s from a randomly selected number.[133,166] (Appendix B) The individual was awarded a check mark for each correct month of the year he or she recited. If a month was skipped, that month was considered an incorrect answer. The five-letter word had to be spelled correctly backwards to receive a correct score. Any error in spelling was counted as incorrect. Similarly, each number subtracted correctly was considered correct; however, if the individual said an incorrect number, but later corrected the pattern, the subsequent answer would be counted as correct. For example, if the task was to subtract by 7s, and the individual said "100, 93, 87, 80…," 87 would be marked as incorrect, since it was only 6 less than 93, but 80 would be counted correct. There were no prioritization instructions given for the cognitive or motor task. There were 4 trials performed under the DT condition, and the order of cognitive tasks was randomized each time.

Data Analysis and Statistical Approach

This study utilized a within and between-subjects prospective longitudinal approach, during which post-concussion postural control parameters were compared at multiple clinical milestones throughout the concussion recovery process. The independent variables were group (concussion, control) and time (Baseline, Acute, Asymptomatic, RTP). The dependent variables for tandem gait included 1) the best overall time of the four trials (BEST), and 2) the mean of the four trials (MEAN). During the DT conditions, in addition to the BEST and MEAN times, two cognitive variables were assessed: cognitive accuracy (i.e. the percentage of correct answers out of the total possible answers), and the total number of correct answers.

Demographic data for the study participants were compared between groups using independent sample t-tests. The dependent variables of interest were compared utilizing six linear mixed-effects model (ST BEST, ST MEAN, DT BEST, DT MEAN, cognitive accuracy, and total number of correct answers). Any significant group x time interactions were followed up with post-hoc testing for fixed effects, which allowed for examination of between group differences.

The efficacy measures (sensitivity, specificity, positive predictive value, negative predictive value) were calculated on the basis of the clinically diagnosed classification of "concussion/no concussion," with the control participants representing the "no concussion" group.

A receiver operating characteristic (ROC) analysis was performed to identify the trade-off between sensitivity and specificity for TG and BESS. The diagnostic accuracy of the dependent variables was calculated using the area under the curve (AUC) for the ROC. We utilized the following criteria values to determine the accuracy of the AUC to distinguish between groups following concussion: 1.00-0.90, *excellent;* 0.89-0.80, *good;* 0.79-0.70, *acceptable;* 0.69-0.60, *poor;* and below 0.59, *failure*.[234] Statistical significance was set at alpha < 0.05, and all statistical models were performed with SPSS Statistics Version 25 (IBM Corp, Armonk, NY).

Results

All 65 of the concussion participants had ST TG and 38 had both ST and DT, as 27 were tested prior to the addition of the DT TG protocol. All 28 of the control subjects had both ST and DT TG. All of the raw ST/DT TG and BESS data can be found in Appendix F.

Time Points	Concussion	Controls
Injury to Acute	1.90 ± 0.40	1.92 ± 0.40
Acute to Asymptomatic	10.60 ± 13.00	19.90 ± 11.26
Asymptomatic to RTP	6.78 ± 7.18	7.82 ± 8.13

Table 2. Mean ± SD of the number of days between testing time points. There were no significant differences between groups for injury to acute (p= 0.50), or acute to asymptomatic (p= 0.62). There was a significant difference between groups for asymptomatic day to RTP (p=0.03).

Single-Task BEST Tandem Gait

There was a significant group x time interaction (F= 3.136, p= 0.026) for ST BEST tandem gait completion time. There was not a significant difference between the concussion and control groups at baseline (p= 0.983), asymptomatic day (p= 0.093), or RTP day (p= 0.187). There was a significant difference between groups at the acute time point (p <0.001). (Figure 9)

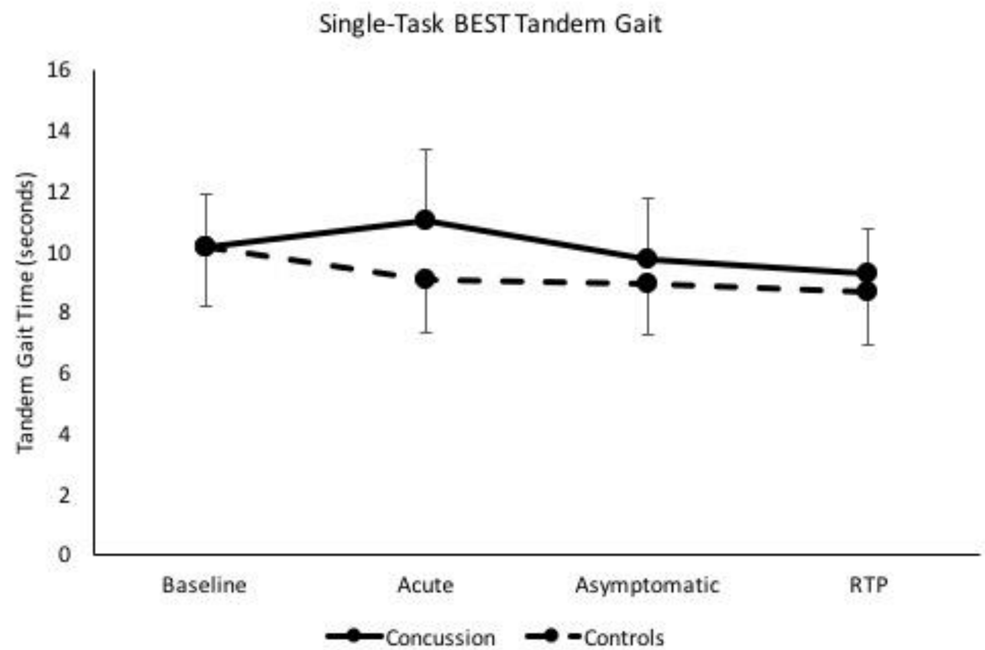

Figure 9. Significant group x time interaction for ST BEST TG performance across time.

There were significant group (F= 13.039, p <0.001) and time (F= 6.154, p < 0.001) effects during ST BEST TG. The group and time effect tables can be found in the Appendix. (Appendix G)

Dual-Task BEST Tandem Gait

There was not a significant group x time interaction for DT BEST TG (F= 2.463, p= 0.063).

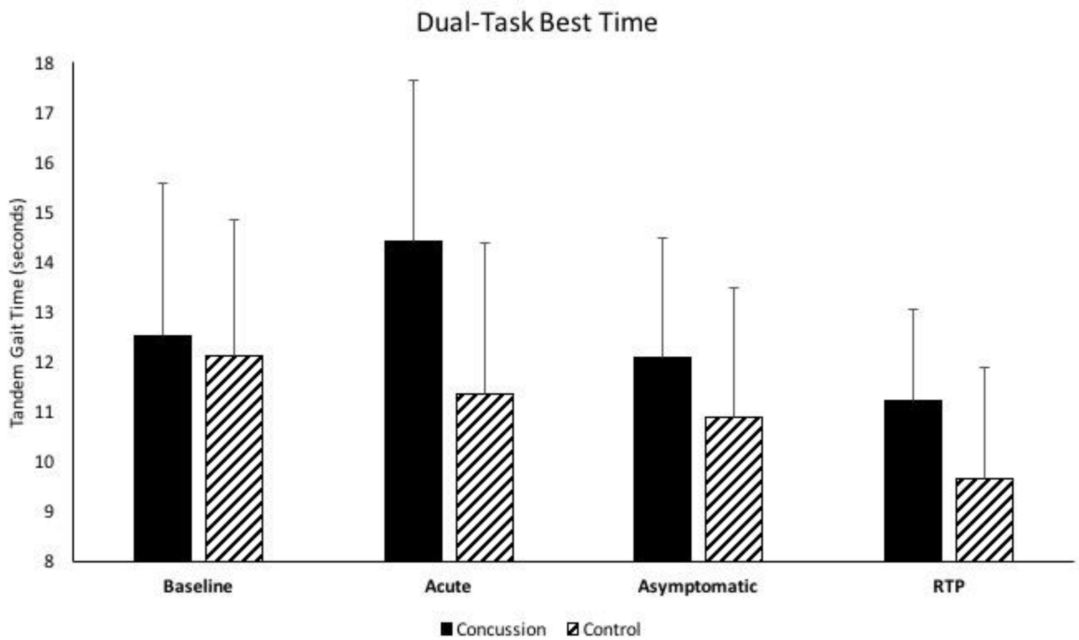

Figure 10. Dual-task BEST TG performance across the four time points.

There were significant group (F= 17.490, p <0.001) and time (F= 7.931, p < 0.001) effects during DT BEST TG. The group and time effect tables can be found in Appendix G.

Single-Task MEAN Tandem Gait

There was a significant group x time interaction (F= 2.983, p= 0.032) ST MEAN TG. There was not a significant difference between the concussion and control groups at baseline (F= 0.140, p= 0.708), asymptomatic day (F= 2.702, p= 0.101), or RTP day (F= 3.202, p= 0.075). There was a significant difference between groups at the acute time point (F= 18.721, p= <0.001). (Figure 11)

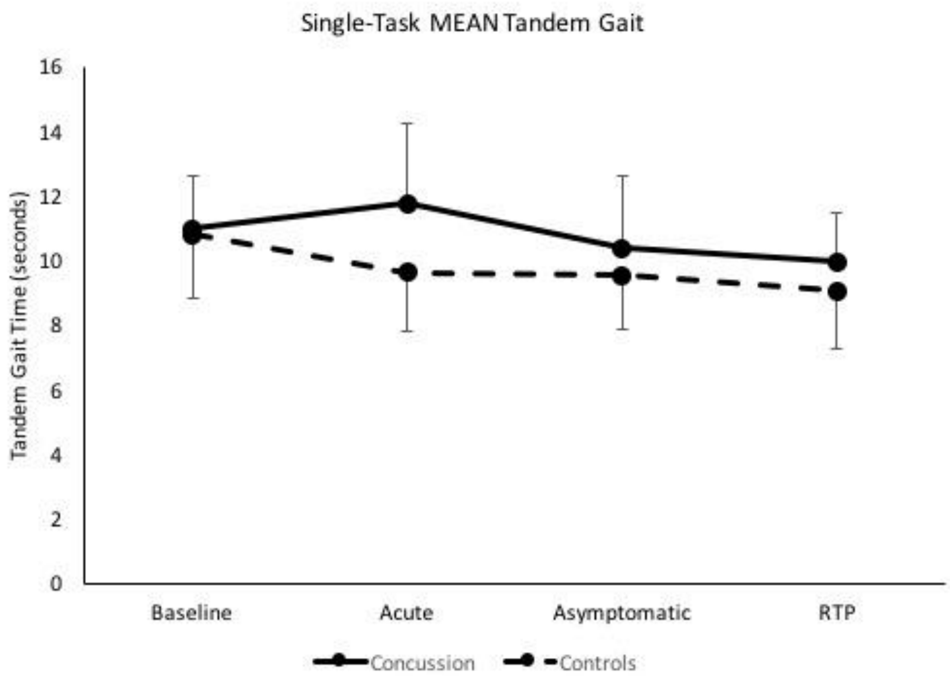

Figure 11. Significant interaction for ST MEAN TG across time.

There were significant group (F= 17.128, p < 0.001) and time (F= 7.211, p < 0.001) effects during ST MEAN TG. The group and time effects table can be found in the Appendix. (Appendix G)

Dual-Task MEAN Tandem Gait

There was not a significant group x time interaction for DT MEAN TG (F= 2.006, p= 0.114).

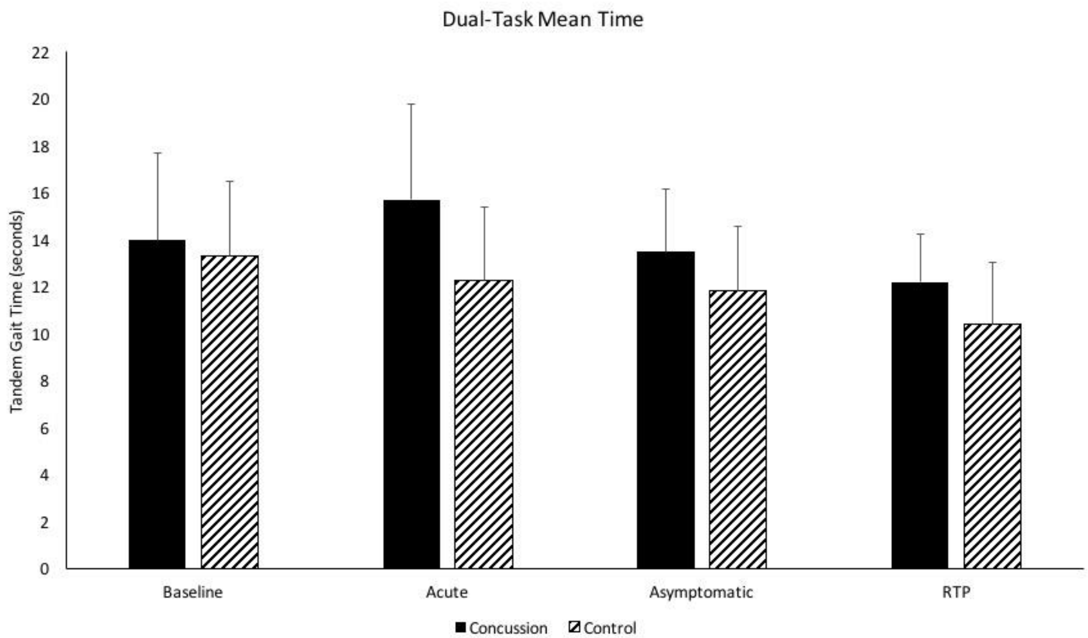

Figure 12. Dual-task MEAN TG performance across the four time points.

There were significant group (F= 19.320, p <0.001) and time (F= 7.595, $p <$ 0.001) effects during DT MEAN TG. The group and time effects table can be found in Appendix G.

Cognitive Performance

There was not a significant group x time interaction for cognitive accuracy (F= 0.075, p= 0.973) or total number of correct answers (F= 1.550, p= 0.203) during DT TG.

		Concussion		Controls	
		n	**Mean ± SD**	***n***	**Mean ± SD**
Total Correct	**Baseline**	38	19.32 ± 6.74	28	20.82 ± 7.04
	Acute	31	23.94 ± 7.66	25	20.64 ± 6.28
	Asymptomatic	31	23.00 ± 8.89	21	19.48 ± 7.37
	RTP	26	23.38 ± 7.61	23	21.30 ± 5.51
Cognitive Accuracy	**Baseline**	38	90.20 ± 9.97%	28	90.82 ± 11.82%
	Acute	31	91.01 ± 10.76%	25	91.41 ± 12.46%
	Asymptomatic	31	92.38 ± 9.80%	21	92.81 ± 11.23%
	RTP	26	96.30 ± 5.22%	23	98.30 ± 2.49%

Table 15. Mean ± SD of total number of correct dual-task answers during TG in the concussion and control groups across the four time points. The "*n*" columns include the number of participants for both conditions at each time point.

There was a significant effect for time (F= 5.031, *p*= 0.002) for cognitive accuracy. (Table 16) There were no significant group or time effects for total number of correct answers.

			95% Confidence Interval		Mixed Model	
Time	**Mean**	**Standard Error**	**Lower Bound**	**Upper Bound**	**F**	***p***
Baseline	90.5	1.2	88.1	92.9	5.031	0.002
Acute	91.2	1.3	88.6	93.8		
Asymptomatic	92.6	1.4	89.9	95.3		
RTP	97.3	1.4	94.5	100.1		

Table 16. Significant time effect for cognitive accuracy during DT TG. There was no difference from baseline to acute (p= 0.697). There was not a significant difference between baseline and asymptomatic (p= 0.262). There was a significant difference between baseline and RTP (p<0.001).

BESS

There was not a significant group x time interaction (p= 0.387, F= 1.013) for BESS scores. There were significant group (F= 41.109, $p < 0.001$) and time (F= 3.037, $p < 0.001$) effects. (Table 17 A and B)

A.

			95% Confidence Interval		Mixed Model	
Group	**Mean**	**Standard Error**	**Lower Bound**	**Upper Bound**	**F**	***p***
Concussion	12.1	0.4	11.3	12.8	41.109	0.001
Controls	7.8	0.5	6.7	8.9		

B.

			95% Confidence Interval		Mixed Model	
Time	**Mean**	**Standard Error**	**Lower Bound**	**Upper Bound**	**F**	***p***
Baseline	11.0	0.6	9.8	12.2	3.037	0.029
Acute	10.9	0.7	9.5	12.2		
Asymptomatic	9.0	0.7	7.7	10.4		
RTP	8.9	0.7	7.5	10.2		

Table 17. A: Significant group effect for BESS. B: Significant time effect for BESS. There was no difference from baseline to acute (p= 0.890). There was a significant difference between baseline and asymptomatic (p= 0.033), and baseline and RTP (p= 0.020).

Efficacy Measures

A comparison of efficacy measures for ST/DT BEST TG, MEAN TG, and BESS can be seen in Tables 18 and 19.

		BEST		MEAN	
	Metric	ST (95% CI)	DT (95% CI)	ST (95% CI)	DT (95% CI)
Acute	Sensitivity	53.5% (37.7% - 68.8%)	66.7% (47.2%-82.7%)	51.2% (35.5%-66.7%)	56.7% (37.4%-75.5%)
	Specificity	92.0% (73.8% - 99.0%)	68.0% (46.5%-85.1%)	100% (86.3%-100%)	84% (63.9%-95.5%)
	Positive Likelihood Ratio	6.69 (1.72 - 26.00)	2.08 (1.12 – 3.89)	-----	3.54 (1.37-9.17)
	Negative Likelihood Ratio	0.51 (0.36 – 0.71)	0.49 (0.28 – 0.87)	0.49 (0.36-0.66)	0.52 (0.33-0.80)
	Positive Predictive Value	92.0% (74.7% - 97.8%)	71.4% (57.2% -82.4%)	100%	80.95% (62.15%-91.67%)
	Negative Predictive Value	53.5% (45.0% - 61.8%)	62.95% (48.9%-75.1%)	54.4% (46.72%-61.78%)	61.8% (50.9%-71.6%)
	AUC	0.723 (0.605-0.841)	0.732 (0.597-0.867)	0.717 (0.597-0.836)	0.732 (0.598-0.866)
Asymptomatic	Sensitivity	27.5% (15.9% - 41.7%)	44.8% (26.5%-64.3%)	27.5% (15.9%-41.7%)	44.8% (26.5%-64.3%)
	Specificity	81.0% (58.1% - 94.6%)	71.4% (47.8%-88.7%)	85.7% (63.7%-97.0%)	81.0% (58.1%-94.6%)
	Positive Likelihood Ratio	1.44 (0.54 – 3.87)	1.57 (0.71 – 3.45)	1.92 (0.62-6.00)	2.35 (0.89-6.21)
	Negative Likelihood Ratio	0.9 (0.69 – 1.17)	0.77 (0.50 – 1.18)	0.85 (0.66-1.08)	0.68 (0.46-1.00)
	Positive Predictive Value	77.8% (56.6% - 90.4%)	68.4% (49.6%-82.7%)	82.4% (59.9%-93.6%)	76.5% (55.2%-90.0%)
	Negative Predictive Value	31.5% (26.2% - 37.5%)	48.4% (38.0%-58.9%)	32.7% (27.6%-38.3%)	51.5% (41.9%-61.0%)
RTP	Sensitivity	30.4% (17.7% - 45.8%)	29.2% (12.6% -51.1%)	26.1% (14.3%-41.1%)	29.2% (12.6%-51.1%)
	Specificity	95.7% (78.1% - 99.0%)	91.3% (72.0% -98.9%)	91.3% (72.0%-98.9%)	95.7% (78.1%-99.9%)
	Positive Likelihood Ratio	7.00 (0.98 – 50.00)	3.35 (0.78 – 14.50)	3.00 (0.73-12.30)	6.71 (0.89-50.36)
	Negative Likelihood Ratio	0.73 (0.59 – 0.90)	0.78 (0.58 – 1.03)	0.81 (0.65-1.00)	0.74 (0.56-0.97)
	Positive Predictive Value	93.3% (66.2% - 99.0%)	77.8% (44.8% -93.8%)	85.7% (59.4%-96.1%)	87.5% (48.3%-98.1%)
	Negative Predictive Value	40.7% (35.8% - 45.9%)	55.3% (48.1% -62.2%)	38.2% (33.3%-43.3%)	56.4% (49.7%-62.9%)

Table 18. Efficacy measures for ST/DT BEST and MEAN TG.

	Measure	BESS (95% CI)
Acute	Sensitivity	38.1% (23.6% - 54.4%)
	Specificity	56% (34.9% - 75.6%)
	Positive Likelihood Ratio	0.87 (0.48 – 1.56)
	Negative Likelihood Ratio	1.11 (0.73 – 1.68)
	Positive Predictive Value	59.26% (44.7% - 72.3%)
	Negative Predictive Value	35% (26.1% - 45.1%)
	AUC	0.427 (0.291-0.563)
Asymptomatic	Sensitivity	28.9% (17.1% - 43.1%)
	Specificity	75% (50.9% - 91.3%)
	Positive Likelihood Ratio	1.15 (0.48 – 2.76)
	Negative Likelihood Ratio	0.95 (0.70 – 1.29)
	Positive Predictive Value	75% (55.7% - 87.8%)
	Negative Predictive Value	28.9% (23.0% - 35.5%)
RTP	Sensitivity	34.8% (21.4% - 50.3%)
	Specificity	65.2% (42.7% - 83.6%)
	Positive Likelihood Ratio	1.00 (0.50 – 1.98)
	Negative Likelihood Ratio	1.00 (0.69 – 1.44)
	Positive Predictive Value	66.7% (50.2% - 79.9%)
	Negative Predictive Value	33.3% (25.8% - 41.9%)

Table 19. Efficacy measures for BESS

Discussion

The TG task has been included in the SCAT as an alternative to the BESS for post-concussion postural control assessment; however, it has received limited attention, particularly in how performance changes following concussion.[159,165,166,235] This investigation is the first to evaluate both single and dual-task TG performance, including the BEST and MEAN of the trials, from baseline across the traditional concussion recovery milestones. The primary finding of this study was a worse performance for both BEST and MEAN single-task TG acutely post-concussion. Conversely, no significant changes were observed for the BESS. These differences suggest that TG may be a better suited than BESS to identify acute post-concussion impairments.

There was a significant group-time interaction for both BEST (Figure 9 A and B) and MEAN (Figure 11 A and B) single-task TG. Acutely following concussion, the concussion group performed significantly worse (i.e. took longer) on single-task TG, relative to their baseline performance on both BEST (0.84 sec) and MEAN (0.77 sec), which exceeds the established MDC time (0.38 sec), but is less than previously reported (1.21 sec).[165] Conversely, the control participants' performance slightly improved (0.20 sec) between their first two TG assessments. Furthermore, there was a significant group effect whereby concussion participants were slower (~ 1 sec) at each time point post-concussion. Alterations in dynamic postural control following concussion, as evidenced by a conservative gait strategy, have been repeatedly observed; however, there is limited evidence as to why the impairments exist.[111,114–

[116,124–134,198] While the underlying mechanism behind slower TG performance following concussion is unknown, it is possible that it could be due to the "goal oriented" nature of the task (i.e. successfully completing the task as quickly as possible without stepping off the line).[159] Goal-directed locomotion is thought to be controlled by an indirect motor pathway that regulates movement via the prefrontal cortex, supplementary motor area, and basal ganglia, all of which are areas that have been suggested to be adversely affected by a concussion.[199,200,202,212,236,237] Our findings were consistent with Howell et al., who demonstrated that concussed individuals took longer to complete single-task TG than healthy controls when tested within 72 hours following concussion.[166] The inclusion of baseline data herein, compared to the cross-sectional approach used by Howell, as well as the use of true post-concussion clinical milestones as opposed to specific dates, strengthens our knowledge of post-concussion TG performance. Of clinical importance, is the acknowledgement that both the Howell study and this investigation observed an improvement in TG performance across time in the control populations, which suggests that TG is likely susceptible to a practice effect with repeat administration.[166]

There was not a significant group-time interaction observed for dual-task TG; however, within 48 hours of injury both BEST and MEAN dual-task TG times were approximately two seconds slower (worse) than baseline. (Figures 10 and 12) During level over-ground gait tasks, dual-task challenges have shown more pronounced postural control impairments than single-task gait; thus, it was not surprising that a dual-task environment resulted in a larger time deficit.[133,166,188,189] Both the total number of correct answers and the cognitive accuracy improved from baseline to acute in the concussion group; thus, the slower times could be a result of task prioritization, whereby the individuals are electing to slow the motor task in order to facilitate the cognitive task. (Table 15) Increased activation in the cerebellum has been observed under dual-task conditions, which could also be influencing the cognitive-motor relationship following concussion, as TG is thought to be critical for coordinating and controlling balance.[114,217,230–232] Our baseline BEST dual-task TG time (12.5 seconds) was highly consistent with Howell's normative reference of 12.6 seconds.[233] As observed during single-task TG, the healthy controls improved at the acute time point for both BEST and MEAN times likely due to a practice effect from repeat administration. A significant time effect demonstrated that both BEST and MEAN dual-task TG times slowed at the acute time point before improving across asymptomatic day and RTP. (Appendix G) Oldham et al., observed a significant order effect, with improvement in TG performance across the four recommended trials; therefore, it would appear this improved performance across trials can potentially be extrapolated out across multiple testing sessions. Future investigations should examine TG time across trials to determine how many repetitions are necessary before reaching a plateau in performance.

Improved performance, secondary to repeat administration, is characteristic of the clinical concussion battery as a whole, but specific to postural control assessment, a notable practice effect is trademark of the BESS.[72,223] Herein, there was no significant group-time interaction for the BESS, and scores improved by ~3.5 errors from baseline (13.6 errors) to RTP (10 errors) in the concussion group. These results resemble Oldham et al., who identified a worsening of 1.2 seconds in TG, but an improvement in BESS performance acutely post-concussion.[165] Consistent with larger studies, McCrea et al., reported an approximately 1.0 error increase in BESS scores at 48 hours post-concussion in NCAA collegiate student-athletes whereas herein we noted a nearly identical performance (0.1 errors) between baseline and acutely post-concussion.[13,178] As observed with TG, there was an improvement in BESS performance of the concussion group following the acute time point through RTP. (Appendix F, Table 17 A and B) The BESS is a novel assessment that examines postural control during quiet stance, which is more reliant on sensory feedback than dynamic gait tasks that rely more on feedforward control.[114,125,126,140,230,238] While there is novelty in a TG task, the nature of the heel-to-toe motion makes it a highly-coordinated movement that is likely to demonstrate post-concussion impairments, based on the role of the motor cortex in regulating balance and posture during such movements.[114,165,230–232] Therefore, it was not surprising to see more deficits in TG compared to BESS following injury.

While group means are important, clinical decisions are made on an individual basis; thus, the test efficacy is arguably more valuable. Herein, both BEST and MEAN ST and DT TG presented with higher overall efficacy than the BESS. (Tables 18 and 19) The acute sensitivity (true positive) of the TG variables ranged from 0.51 to 0.67 where the BESS was 0.38, which is similar to previous reports.[165,178] The lowest acute specificity (true negative) of the TG measures was 0.68 while the BESS was 0.56, which is marginally higher than the 0.50 previously identified by Oldham et al., and substantially lower than McCrea et al.'s 0.91 specificity at 48 hours post-concussion.[178] In addition, the AUC for all four TG measures (range: 0.71-0.73) was classified as "acceptable" acutely post-concussion, whereas the BESS (0.43) classified as a "fail."[234] (Tables 18 and 19) For a clinician, the positive and negative predictive values of a test, which indicate the percentage of individuals who truly do (PPV) or do not (NPV) have the disease after testing positive or negative are just as important as sensitivity and specificity.[239] The best PPV was ST MEAN TG acutely post-concussion, which had a perfect 100% for identifying those who tested positive for concussion (i.e. failed TG) and were actually concussed. Conversely, the lowest PPV was the BESS (59%) acutely post-concussion, further demonstrating that TG may be a stronger assessment in identifying acute impairments. (Tables 18 and 19) This study is the first to investigate efficacy measures of DT TG, and while the acute DT PPVs were not as high as ST, the NPVs were higher, suggesting DT is potentially more useful in identifying those who are healthy. (Table 18) Overall, TG appears to have better psychometrics for identifying post-concussion impairments.

Tandem gait was originally utilized as a general balance test when examining cerebellar function, and impairments have been localized to abnormalities in the cerebellar vermis, flocculonodular lobe, and a disconnect between the cerebellar pathways and brainstem nuclei.[240–245] Although different underlying pathologies, TG has also displayed deficits in those with Huntington's Disease, Parkinson's disease, and peripheral neuropathies.[243,246–249] Successful postural control requires the integration of visual, vestibular, and somatosensory systems, and it has been suggested that postural control impairments could result from a deficit in sensory interaction, which has routinely been observed following concussion.[69,114,250] Reduced sensory interaction has also been observed via decreased activation in healthy young adults in vestibular and somatosensory areas during locomotion and increased activation in visual cortical areas.[212,236] Tandem gait has traditionally been considered a vestibular assessment; thus, it is possible that slower TG times could result from this impaired vestibular function being exacerbated following concussion due to the spreading depression and energy crisis initiated by the neurometabolic cascade.[27] It is also possible that altered TG performance may be related to an individual's ability to control frontal plane movement.[166] Howell et al., identified moderate to high correlations between frontal plane movement and mean TG time, suggesting that those who took longer to perform TG displayed greater mediolateral center of mass displacement.[166] Mediolateral balance impairments have been thought to be the reason for abnormal TG in those with Parkinson's; thus, while the fundamental neuropathologies of concussions and Parkinson's are inherently different, it appears they might initially result in similar postural control impairments during TG.[243]

Tandem gait abnormalities have traditionally been determined as an inability to successfully perform TG (i.e. taking multiple steps off of the designated line); however, as a post-concussion assessment, time has clinically been the primary TG outcome. Herein, and as expected, we observed slower post-concussion TG times during both single-task and dual-task conditions suggesting impaired postural control.[165,166] Although TG was slowed following concussion, there were no instances where an individual could not successfully complete the TG task following injury, as seen in the aforementioned populations with more advanced neurological disorders. This is clinically relevant, as the TG guidelines have recently changed from the best of four timed trials in the SCAT-3 to a subjective "yes" or "no" response to whether or not an individual can perform TG normally, which is not defined, in the SCAT-5.[160,221] The TG protocol has developed over the last decade, starting with Schneiders et al., evaluating the mean of three timed TG trials, and progressing to the SCAT-3 evaluating the best of four timed trials.[90,156,221] Despite the lack of evidence-based guidelines for TG procedure, there is a clinical need for a standardized protocol, which has been removed in the SCAT-5.[160] Our results suggest that a subjective response to whether or not TG performance is normal will not be sufficient enough to identify post-concussion postural control impairments, as all of our participants were able to complete TG successfully, albeit slower following injury. Therefore, these results suggest that time to complete TG should be included in clinical assessment, especially under a dual-task condition, as time differences following concussion were more pronounced than single-task.

The acute ST and DT TG assessments herein were completed in a quiet environment within 48 hours post-concussion; thus, sideline applicability should not be interpreted. This investigation focused solely on collegiate student-athletes, and extrapolations to other populations (i.e. youth, high school) should be cautiously considered. Preliminary research in a high school population demonstrated that the majority of athletes were unable to complete single-task TG in the 14 second cutoff suggested by the SCAT-3; however, future research is needed among those populations to determine how TG performance changes over time following concussion. Further, this study utilized mostly non-athlete controls, as it was challenging to recruit healthy student-athletes for multiple testing sessions; thus, it should be a priority in future research to match concussed athletes to non-injured athletes as closely as possible. Although controlled for by the mixed model statistical approach, the amount of missing data across concussion time points was a limitation of this investigation; however, the missing data provides clinicians with a realistic approach to post-concussion recovery assessment, as there are any number of confounding factors that cause a student-athlete to miss follow-up time points. We did not include foot size in this investigation, which has the potential to be an influencing factor in TG time, but our within-subjects approach allowed us to provide consistency across anthropometric measures.

Tandem gait is a clinically feasible, but underutilized, postural control assessment following concussion.[165,166] Performance on both single and dual-task TG was worse acutely post-concussion, compared to both baseline values and healthy controls. Conversely, there was no change in BESS performance acutely post-injury, which suggests TG may be a more robust postural control assessment for identifying impairments acutely concussion. Further, the overall efficacy of TG was better than the BESS, particularly acutely post-injury. While a practice effect appears to influence TG performance over time, it is a valuable assessment with strong psychometric properties in identifying acute postural control impairments and can be utilized in a clinical setting.

Chapter 4

THE ASSOCIATION BETWEEN CONCUSSION AND SUBSEQUENT LOWER EXTREMITY MUSCULOSKELETAL INJURY RISK

Introduction

There are an estimated 1.6-3.8 million occurrences of concussions annually in the United States, and both the NIH and the CDC have classified concussion as a major health disorder.[167,168] Additionally, concussions are estimated to have an economic burden of approximately $22 billion annually.[168] Nearly 500,000 athletes participate in NCAA sports; thus, the number of individuals are at risk for concussion is significant.[251] Concussions pose serious health risks, both acutely and chronically. Acutely following concussion, there is an elevated risk recurrent concussion, as an individual is more likely to sustain a subsequent concussion if he or she returns to participation within the first 7-10 days after the original injury.[32] A concussion also puts an individual at risk for second impact syndrome, which is a rare, but potentially fatal condition.[169–171] Further, those with a concussion history are 3-5x more likely to sustain a future concussion compared to those with no history, and are at risk for a number of long-term risks, such as later life depression, dementia, early onset Alzheimer's, and chronic traumatic encephalopathy.[41,53,61,62,174,175] These potential short term and long term risks demonstrate that concussions pose as a health threat across an individual's entire lifespan.

The current post-concussion return to play assessment utilizes a multifaceted approach that incorporates a battery of self-reported symptoms, cognitive, and postural control examinations.[29] While many of the assessment techniques are highly sensitive (0.89-0.96) for acute concussion diagnosis, the sensitivity drops significantly (0.30) within the first seven days following injury, largely due to practice effects from repeat administration, therefore making the multifaceted battery an insufficient indicator of concussion recovery.[67,178] Impaired postural control is one of the cardinal symptoms of concussion, and the currently recommended postural control assessment is the Balance Error Scoring System (BESS).[29,252] The BESS is a novel assessment that examines postural control during three different quiet stances on firm and foam surfaces.[179] Despite the frequent use of the BESS across clinical settings, it has multiple limitations. Most notably, the test has a significant practice effect with repeat administration.[224] Further, the BESS has unacceptably low sensitivity (0.34), even acutely post-concussion, and poor psychometric properties, including low interrater (0.57) and intrarater (0.74) reliability and high minimum detectable change scores (7.3-9.4 errors) that exceed normal post-concussion change.[178,180,181] Typically, BESS scores return to baseline within 3-5 days following concussion, which is prior to 5-7 days of symptom resolution.[13] Therefore, the BESS alone is not sufficient for the identification of concussion recovery. Further, the BESS evaluates postural control in a quiet stance realm, with the end goal being to maintain upright balance, but it has been suggested that dynamic tasks are better suited to identify deficits following concussion.[125]

Gait is an innate, dynamic task that has demonstrated to be a reliable method in evaluating postural measures, and the latest Consensus Statement on Concussion in Sport has recommended that gait evaluations be included within the neurological exams following injury.[29] Evidence of alterations in gait, demonstrated by metrics such as slower gait velocity, reduced horizontal separation of the COP-center of mass (COM), and increased double support time have been observed acutely post-concussion and up to 2 months following injury, particularly under dual-task conditions, which suggests the presence of an overall conservative gait strategy that persists beyond typical post-concussion clinical recovery.[111,124–134] It is possible that this persistent alteration in gait strategy is due to an incomplete neural recovery, as the physiological control of gait is thought to be rooted in higher level centers that have demonstrated to be affected by concussive injuries.[111,114–116,124–134,198] While this conservative gait strategy exists following concussion, it is unknown as to how it affects individuals long term.

There is increasing evidence of a relationship between concussion and subsequent lower extremity musculoskeletal (LEMSK) injury across a variety of populations.[97–106,253,254] In collegiate athletes, a 1.64-2.48 elevated risk of injury exists within the 365 days following a concussion.[98,100,102] A similar risk has been identified in professional athletes (1.47-2.23) and more recently, high school athletes (1.34).[97,99,101,103,104,254] The elevated risk of subsequent injury is consistent across a wide variety of sports (i.e. contact/non-contact), as well as across both males and females; thus, there do not appear to be any obvious risk factors based on specific athlete characteristics.

While the research is convincing that an association between concussion and subsequent LEMSK exists, the underlying reason behind the elevated risk remains unknown. One of the original theories was the possibility that certain individuals are simply more injury prone than others, as multiple studies have demonstrated an increased risk of sustaining an injury in the year prior to concussion; however the literature remains mixed.[100–102] Another speculation behind the increased injury risk is the presence of deficits in postural control following concussion.[98–100,105,107] These deficits could be resulting from a disruption of cortical pathways that would interfere with the ability to control and coordinate movements.[100,103] Further, a disconnect in sensory interaction has been observed following concussion, which could result from an inability to successfully coordinate the somatosensory systems with the motor and cognitive systems, and therefore lead to impairments in postural control.[114,255]

There is increasing evidence that a relationship exists between concussion and subsequent lower extremity musculoskeletal injury; however, the underlying mechanism behind this connection has yet to be elucidated. The purpose of this investigation was to examine the relationship between concussion and subsequent injury. Further, impaired postural control has been speculated as a possible influence in the elevated post-concussion injury risk; therefore, a secondary purpose of this study was to evaluate gait variables as potential predictors of subsequent injury. We hypothesized that individuals who suffered a concussion would have an increased incidence of lower extremity musculoskeletal injury in the following year. Our secondary hypothesis was that the gait-related independent variables would predict injury incidence.

Specific Aim 3: Description

Aim 3A: *To investigate the association between concussion and subsequent lower extremity musculoskeletal risk.*

Aim 3B*: To investigate the role of gait variables as predictors for subsequent injury*

H1. Individuals who suffer a concussion will have an increased incidence of lower extremity musculoskeletal injuries than matched non-concussed individuals.

H2. Individuals who demonstrate dynamic postural control impairments will have an increased risk of lower extremity musculoskeletal injury.

Methods

Participants

For Aim 3A, there were 103 concussions during the window of data collection. However, only 32 were eligible to be included for injury assessment. The majority of individuals were excluded because the concussion fell outside of the August 2015-February 2017, and we were unable to track subsequent injuries for a full 365 days. timeline All student-athletes and cheerleaders at the University of Delaware who suffered a concussion during the course of their athletic participation were eligible for inclusion in the study, as long as the concussion occurred between August 2015 and February 2017. Both sport-related and non-sport related concussions were included in the analysis. Individuals were excluded from the study if the injury required hospitalization, or resulted in positive neuroimaging findings. All concussions were initially assessed by a certified athletic trainer and confirmed by a team physician. The 32 eligible concussions were matched with 32 student-athlete controls who did not suffer a concussion, bringing the total number of student-athletes included in the analysis to 64. Matches were made based on sport and position, when possible. Each participant provided oral and written informed consent in accordance with the university's Institutional Review Board (IRB).

	Concussion (n= 32)	Controls (n= 32)
Age (years)	19.9 ± 1.5	21.9 ± 1.0
Height (cm)	177.1 ± 12.0	173.1 ± 53.0
Mass (kg)	78.3 ± 20.8	74.6 ± 19.2
Concussion history (n)	34% (11/32) 0.5 ± 0.6 (range, 0-2)	13% (4/32) 0.3 ± 0.8 (range, 0-1)
Sex (M/F)	16/16	16/16
Sport Breakdown	Baseball Football Field Hockey Men's Lacrosse Women's Lacrosse Men's Soccer Women's Soccer Tennis Softball Men's Basketball Women's Basketball Track and Field Rowing Cheerleading Volleyball	Baseball Football Field Hockey Men's Lacrosse Women's Lacrosse Men's Soccer Women's Soccer Tennis Softball Men's Basketball Women's Basketball Track and Field Rowing Cheerleading Volleyball
Injury Breakdown	**29/32 (91%) were injured** Ankle: 34% Knee: 31% Hamstring: 10% Other: 25%	**21/32 (66%) were injured** Ankle: 33% Knee: 33% Hip: 10% Other: 24%

Table 20. Aim 3A demographics. There were no significant differences between groups for age (p= 0.63), height (p= 0.56), or weight (p= 0.24).

For Aim 3B, there were 34 participants included in the gait group and 65 participants included in the tandem gait group. The 34 participants are the same demographics as Aim 1 (Table 1), and the 65 are the same demographics as Aim 2 (Table 14). Any student-athlete utilized in Aims 1 and 2 were additionally consented to participate in this study during the preseason baseline testing. Individuals were included in the analysis if 1) he or she had both baseline and post-concussion data for gait and/or tandem gait and 2) a timeframe of at least a year post-concussion to track subsequent injury data. Both sport-related and non-sport related concussions were included in the analysis. Each participant provided oral and written informed consent in accordance with the university's Institutional Review Board (IRB).

Procedures

Injuries were tracked using the SportsWareOnLine (SWOL) injury database. The definition of injury given by the NCAA's Injury Surveillance System states that a reportable injury must 1) occur as a result of participation in an organized intercollegiate practice or competition, 2) require attention from the team athletic trainer of physician, and 3) result in restriction of participation for 1 or more days.[256] Our definition of injury was consistent with the NCAA, with the exception that we also included non sport-related concussions. Injuries were classified by three major categories: mechanism (acute vs chronic), location (ankle, knee, etc), and type (sprains, fractures, etc). All injuries were recorded, but only acute injuries were included in the statistical analysis.

Data Analysis and Statistical Approach

During this investigation, we prospectively examined subsequent lower extremity musculoskeletal injuries in individuals concussed during their time as a student-athlete. For Aim 3A, the dependent variable was the time to the first lower extremity injury, and the independent variable was categorical (concussion or no-concussion).

For Aim 3B, the dependent variable was categorical (injured or non-injured). The independent predictor variables included 1) ST/DT APA duration, 2) ST/DT first step duration, 3) ST/DT first step range of motion, 4) ST/DT peak forward APA, 5) ST/DT peak lateral APA, 6) ST/DT gait speed, 7) ST/DT double support time, 8) ST/DT cadence, 9) ST/DT stride length, 10) ST/DT best tandem gait time, and 11) ST/DT mean tandem gait time.

Demographic data for the study participants were compared between groups using independent sample t-tests. For Aim 3A, we utilized a Cox-Proportional Hazard Model to determine if concussion increased the risk of lower extremity musculoskeletal injury in the next year. For Aim 3B, we utilized 1) a linear mixed effects model to identify any significant interactions or main effects between those who were injured and not injured for the ST and DT gait-related independent variables and 2) a binary logistic regression to evaluate if any of the dependent variables from Aims 1 and 2 were predictors of subsequent injury in the year following concussion. Statistical significance was set at alpha < 0.05, and all statistical models were performed with SPSS Statistics Version 25 (IBM Corp, Armonk, NY).

Results

Aim 3A: Injury Risk

There was a significant risk of acute lower extremity injury in the concussion group, compared to controls, the year following concussion (HR: 1.82, p= 0.037, 95%CI: 1.04-3.20). (Figure 13)

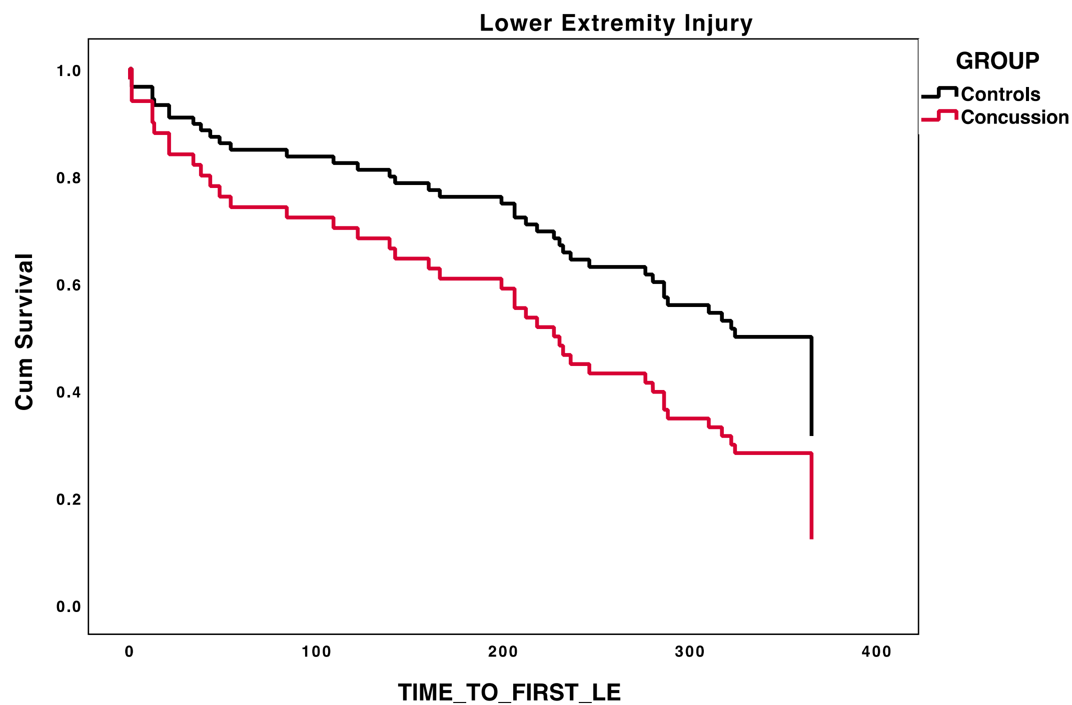

Figure 13. Cox proportional hazard model for injury risk between concussion and no concussion groups

Aim 3B: Group Comparison

The raw data for the gait initiation variables can be found in Appendix 8. The raw data for the gait variables can be found in Appendix 9. The raw data for TG can be found in Appendix J.

Gait Initiation

There were no significant group effects for ST APA duration (F= 0.567, p= 0.454), forward peak APA (F= 0.284, p= 0.596), lateral peak APA (F= 3.533, p= 0.064), first step duration (F= 0.051, p= 0.822), or first step ROM (F= 0.785, p= 0.506).

There were no significant group effects for DT APA duration (F= 1.829, p= 0.180), forward peak APA (F= 0.122, p= 0.728), lateral peak APA (F= 1.017, p= 0.316), first step duration (F= 0.734, p= 0.394), or first step ROM (F= 1.337, p= 0.251).

Gait Speed

There was a significant group effect for ST gait speed (F= 6.457, p= 0.013). (Table 21, Figure 14).

			95% Confidence Interval		Mixed Model	
Group	**Mean**	**Standard Error**	**Lower Bound**	**Upper Bound**	**F**	***p***
Injured	1.14	0.11	0.93	1.35	6.457	0.013
Non-Injured	1.21	0.11	0.91	1.51		

Table 21. Significant group effect for single-task gait speed between those who did and did not sustain a lower extremity injury following concussion.

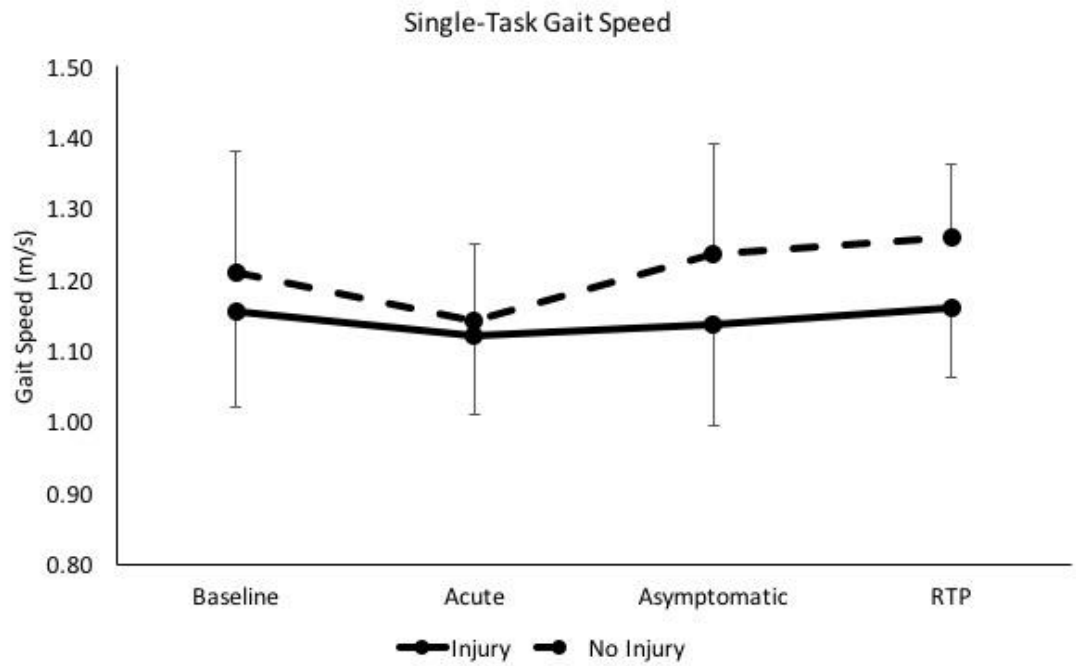

Figure 14. Single-task gait speed in individuals who did and did not sustain a lower extremity injury following concussion.

There was a significant group effect for DT gait speed (F= 8.532, p= 0.004).

(Table 22, Figure 15)

			95% Confidence Interval		Mixed Model	
Group	**Mean**	**Standard Error**	**Lower Bound**	**Upper Bound**	**F**	***p***
Injured	0.99	0.10	0.80	1.18	8.532	0.004
Non-Injured	1.07	0.10	0.85	1.30		

Table 22. Significant group effect for dual-task gait speed (m/s) between those who did and did not sustain a lower extremity injury following concussion.

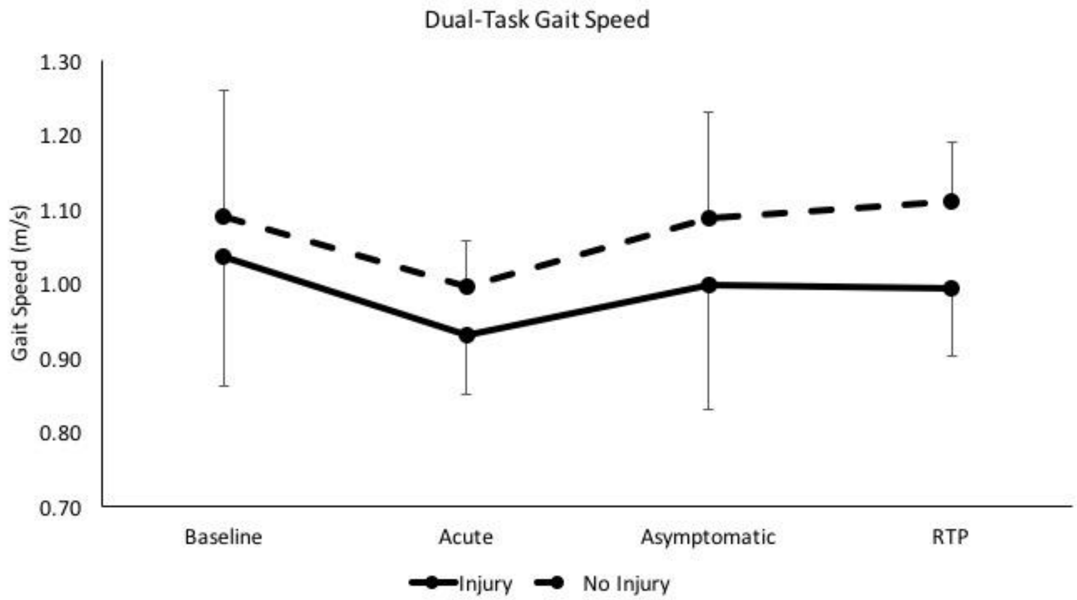

Figure 15. Dual-task gait speed in individuals who did and did not sustain a lower extremity injury following concussion. There was a significant group difference (p= 0.004).

Double Support Time

There was a significant group effect (F= 7.103, p= 0.009) for ST double support time. (Table 23, Figure 16)

			95% Confidence Interval		Mixed Model	
Group	**Mean**	**Standard Error**	**Lower Bound**	**Upper Bound**	**F**	***p***
Injured	19.9	0.4	19.2	20.6	7.103	0.009
Non-Injured	18.4	0.4	17.5	19.2		

Table 23. Significant group effect for single-task double support time (%) between those who did and did not sustain a lower extremity injury following concussion.

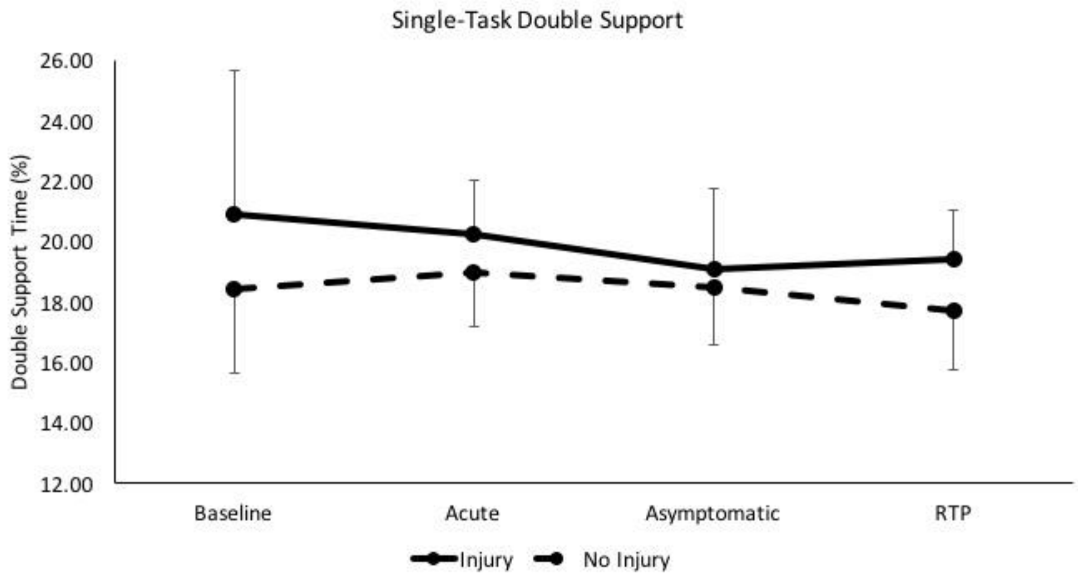

Figure 16. Single-task double support time in those who did and did not sustain a lower extremity injury following concussion.

There was a significant group effect for DT ($F= 10.617$, $p= 0.002$) double support time. (Table 24, Figure 17)

			95% Confidence Interval		Interaction	
Group	**Mean**	**Standard Error**	**Lower Bound**	**Upper Bound**	**F**	***p***
Injured	22.0	0.3	21.3	22.7	10.617	0.002
Non-Injured	20.3	0.4	19.5	21.1		

Table 24. Significant group effect for dual-task double support time (%) between those who did and did not sustain a lower extremity injury following concussion.

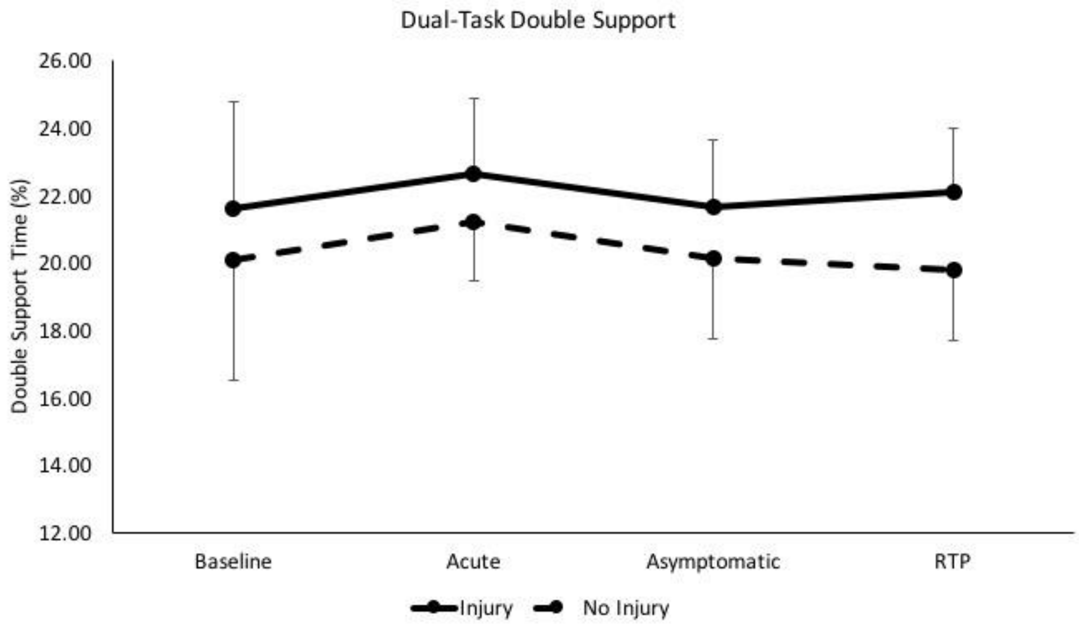

Figure 17. Dual-task double support time in those who did and did not sustain a lower extremity injury following concussion.

Cadence

There was no significant group effect for ST cadence (F= 1.782, p= 0.185), but there was a significant group effect for DT (F= 4.061, p= 0.047). (Table 25, Figure 18)

			95% Confidence Interval		Interaction	
Group	**Mean**	**Standard Error**	**Lower Bound**	**Upper Bound**	**F**	***p***
Injured	105.7	6.2	89.1	122.2	4.061	0.047
Non-Injured	109.2	6.3	97.9	120.5		

Table 25. Significant group effect for dual-task cadence (steps/min) between those who did and did not sustain a lower extremity injury following concussion.

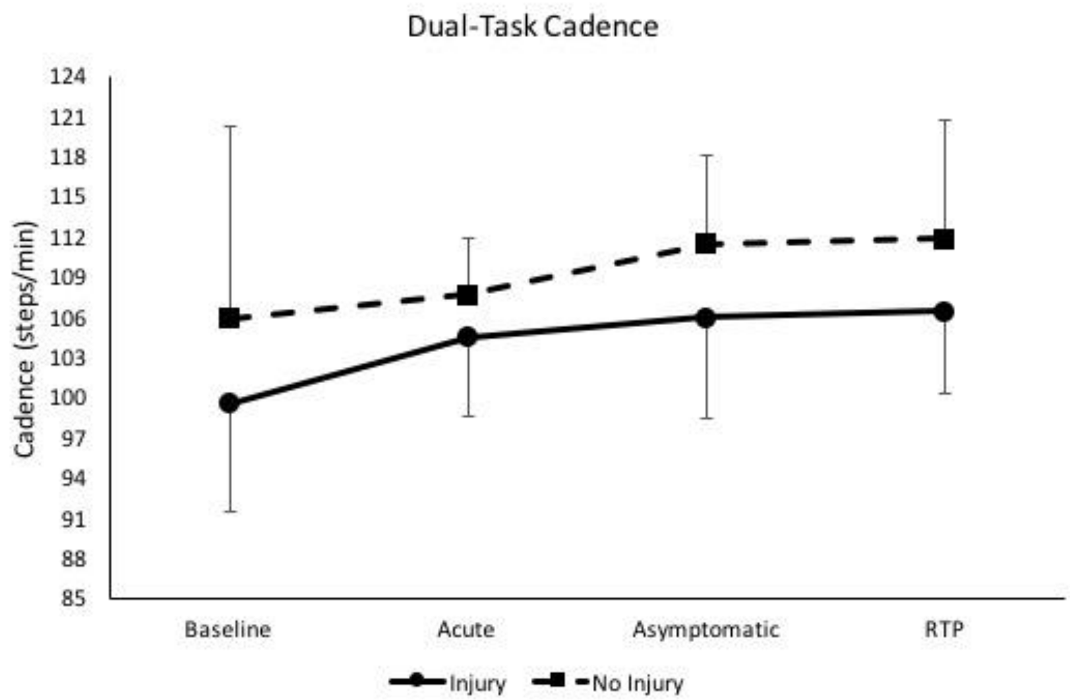

Figure 18. Dual-task cadence in those who did and did not sustain a lower extremity injury following concussion.

Stride Length

There were no significant group effects for ST (F= 2.512, p= 0.116) or DT (F= 3.521, p= 0.064) stride length.

Tandem Gait

There were no significant group effects for ST BEST TG (F= 0.023, p= 0.879) or ST MEAN TG (F= 0.059, p= 0.808).

There were no significant group effects for DT BEST TG (F= 0.146, p= 0.703) or DT MEAN TG (F= 0.196, p= 0.659).

Aim 3B: Binary Logistic Regression

There were no significant predictors of acute lower extremity injury in the year following concussion from the independent variables in the regression model. (Table 26).

	Variable	B	Sig	Exp (B)
Single-Task	APA Duration	0.44	0.83	1.55
	Forward Peak APA	-3.06	0.79	0.05
	Lateral Peak APA	-6.18	0.86	0.002
	First Step Duration	2.55	0.30	1.49
	First Step ROM	0.002	0.97	1.002
	Gait Speed	0.41	0.54	1.51
	Double Support	-0.17	0.55	0.85
	Cadence	0.10	0.37	1.10
	Stride Length	2.46	0.66	1.45
	BEST TG	0.17	0.25	1.19
	MEAN TG	0.24	0.13	1.27
Dual-Task	APA Duration	0.76	0.15	2.13
	Forward Peak APA	60.09	0.06	1.25
	Lateral Peak APA	55.07	0.12	8.25
	First Step Duration	2.43	0.31	1.79
	First Step ROM	-0.068	0.48	0.94
	Gait Speed	-0.81	0.69	0.45
	Double Support	-0.188	0.48	0.83
	Cadence	0.07	0.47	1.08
	Stride Length	-1.44	0.55	0.24
	BEST TG	0.26	0.76	1.03
	MEAN TG	0.02	0.82	1.02

Table 26. Binary logistic regression using change scores from baseline to RTP. A positive change reflects and improvement from baseline at RTP.

Discussion

There is emerging evidence of an association between concussion and subsequent lower extremity musculoskeletal (LEMSK) injury among athletes; however, the underlying mechanism of this relationship remains unknown.[97–106,253,254] This investigation is the first to examine post-concussion ST and DT gait variables as potential predictors for subsequent LEMSK injury. The primary finding of this study was an increased risk (↑1.82x) of acute lower extremity injury in the year following RTP from concussion. Additionally, there were significant differences in ST and DT gait parameters between those who sustained a subsequent injury following concussion and those who did not; however, none of the gait parameters were significant predictors of subsequent injury. While there are a number of proposed theories, the mechanism behind the increased injury rate following concussion remains unclear although the results herein suggest that lingering postural control deficits likely contribute to the elevated risk.

Herein, we observed a 1.82 increased risk (95% CI: 1.04-3.20, p= 0.037) of acute lower extremity injury in the concussion group compared to matched controls across the 365 days following RTP from concussion. (Figure 13) Our results are consistent with prior investigations that observed an increased risk of subsequent lower extremity injury in high school (1.34),[254] collegiate (1.64-2.48)[98,100,105,106] and professional athletes (1.47-2.23).[97,99,101,103,104] Specifically in collegiate student-athletes, a 1.64-2.48 elevated risk of subsequent LEMSK has been observed following concussion; however, the 2.48 was restricted to the first 90 days after concussion.[98,100] We examined injury risk in all of our varsity sports (50% contact/collision, 50% non-contact), and had an even number of males (16/32) 50% and females (16/32) 50%, whereas previous studies in the collegiate population were predominantly male collision sport athletes (e.g., football).[98,100] Our findings extend the existing literature by identifying similar elevated injury rates in both females and non-collision sport athletes. The majority of the injuries seen in both groups were ankle (44%) and knee (41%) sprains, which is consistent with other post-concussion injury data in collegiate athletes.[98,100] (Table 20) Despite the inclusion of a wide variety of athletes in these injury studies, the mechanism of increased subsequent injury risk remains unknown; therefore, our second aim of this investigation was to examine the possibility of gait variables as predictors.

There were significant differences in post-concussion stepping characteristics between those who did and did not sustain a subsequent injury in the next year. The subsequent LEMSK injury group had a significantly slower ST (0.07 m/s) and DT (0.08 m/s) gait speed than those who did not sustain a subsequent injury. (Tables 21 and 22, Figures 14 and 15) Further, the injury group also spent more time in double support during ST (1.5%) and DT (1.7%) conditions. (Tables 23 and 24, Figures 16 and 17) These characteristics of reduced gait speed and increased double support time are similar to those of the conservative gait strategy observed following concussion.[48,124,125,127,134,206,257] Gait speed is thought to be controlled by glutamatergic excitatory neurons that are heavily regulated by the motor action of the basal ganglia, which is a region of the brain that has been adversely affected by concussion.[202,258] In addition, there is evidence of lowered glutamate in the primary motor cortex following concussion;[201] therefore, it is possible that the slower gait speed and overall distinct motor programming of the injury group could be a lingering post-concussion postural control deficits. Impaired postural control has been suggested as a risk factor for sustaining acute ankle sprains, which was one of the most common subsequent injuries we observed in both the concussion and controls groups.[259] Gait measures have successfully demonstrated postural control impairments following concussion, as the physiological control is rooted in higher level centers that are thought to be affected by concussive injuries; thus, if an individual is presenting with an altered gait strategy, it could be a driving factor behind subsequent injury.[111,114–116,124–134,198] Despite differences in postural control, it is also possible that certain individuals are simply more injury prone than others, as increased rates of injury have also been observed in the year prior to concussion in some, but not all, studies.[100–102]

In order to further investigate postural control impairments as a potential cause for elevated injury risk, we examined ST and DT gait variables to identify potential lingering deficits at RTP as predictors of subsequent LEMSK injury. The tertiary finding of this investigation was that there were no significant predictors for any of the ST or DT gait-related independent variables which was the opposite of the a-priori hypothesis. (Table 26) Thus, while there were differences between the injury and non-injury groups for a number of gait variables, the specific variables themselves were unable to identify which individuals were more likely to belong to a specific group.

From our results, we were able to observe that the athletes who presented with a conservative gait strategy tended to belong to the group who went on to sustain a subsequent injury after concussion, but analysis of the individual gait variables did not demonstrate the likelihood of belonging to one group over another (i.e. individuals who walked with a slower gait speed were more likely to be in the injury group, but a slower gait speed did not identify an individual as sustaining an injury or not). Clinically, this is challenging as there is not an individual predictor of subsequent LEMSK injury, but rather it appears that those with an overall conservative gait strategy are the higher re-injury group. Regardless, our study was not able to identify significant predictors of subsequent injury following concussion, so future research should look to other potential variables.

Our results contribute to the growing evidence of a concussion-subsequent LEMSK injury risk, but the underlying reason behind this increased risk of injury has yet to be elucidated. An early hypothesis for the elevated injury risk was impaired postural control secondary to a disruption of cortical pathways that could alter the ability to control and coordinate movement.[100,103] Successful postural control requires a successful integration of the visual, vestibular, and somatosensory systems, as well as the motor and cognitive systems, and it has been suggested that impairments could result from a disconnect in sensory interaction, which has been observed following concussion.[69,250] Working memory tasks require appropriate activation in the prefrontal cortex, which has shown to be adversely affected following concussion.[200,212–216] Increased neuronal activity, identified as elevated BOLD signal on fMRI, in the prefrontal areas occurs during DT gait requires a greater number of neural resources to achieve the same ST results, which suggests that individuals are having to utilize compensatory strategies during DT challenges to achieve the appropriate motor and cognitive output. As the majority of our differences were observed under DT conditions, it is possible that DT challenges may be appropriate risk factors for injury, which lends further support of including DT assessments in routine post-concussion clinical care, as they are not typically included currently.[107] The addition of DT to tandem gait is a clinically feasible method that can be easily implemented across all clinical settings that do not have access to sophisticated instrumentation. Dual-task gait challenges have not only exhibited more pronounced postural control deficits than ST, but these deficits have also demonstrated to linger as far out as 2 months beyond clinical recovery, which could be a factor in subsequent injury.[134,189,194,252] There were significant differences in DT stepping characteristics between the injured and non-injured groups, and poor DT outcomes could be manifesting from incomplete brain recovery, which could be exposing these individuals to further risk of subsequent injury. Howell et al., observed an association between a worsening DT gait cost and time-loss injuries, whereby the group who went on to sustain an injury displayed worse DT cost over time; however, that relationship was not investigated herein.[260] The DT utilized herein was the same task as Howell et al., therefore, future research should focus on a variety of DT challenges to examine the influence of task choice on DT gait and subsequent injury.[260]

As the gait variables did not demonstrate to be significant predictors of the association between concussion and LEMSK injury, other potential causes must be explored moving forward. Prior injury is considered to be one of the leading risk factors for subsequent injury, particularly in the four most common lower extremity injuries (hamstring strain, ACL rupture, Achilles tendon injury, and ankle sprain).[261] As there is mixed evidence of increased injury rate in the year before concussion, this risk needs to be taken into consideration.[100–102] The structure of our data collection did not allow us to investigate injury prior to concussion due to a change in the electronic medical records utilized, so future research should continue to examine injury rates before a concussive injury. Furthermore, we were unable to reliability obtain pre-college injury data on the participants; thus, pre-existing injuries were not explored. Our concussed student-athletes who went on to sustain a LEMSK injury in the next 365 days were out for an average of 18 ± 11 days due to the concussion, which is longer than the 7-10 day window during which the majority recover.[29] Further, 19% (6/32) of the individuals in the concussion group took longer than 28 days to be cleared, which is traditionally classified as prolonged recovery, and all 6 of these individuals sustained a subsequent injury. Future research should examine the relationship between concussion time loss and the rate of subsequent LEMSK injury as prolonged symptoms may be associated with the subsequent injuries. Finally, the psychological, and not just physical, aspect of returning to sport should also be considered as a potential influencer to subsequent injury. Individuals recovering from concussion tend to present with a negative emotional response, particularly elevated anxiety and depression as well as reduced vigor.[262–264] Individuals with anxiety disorders present with increased activity in the emotion-processing regions of the brain, such as the amygdala, which could be influenced by concussion, and could be associated with an increased injury risk.[265,266] Therefore, psychological measures should be evaluated at the time of RTP to help identify any individuals who might need more focused monitoring of mental health.

These results demonstrate that the subsequent LEMSK injury rate was higher in the groups who presented with poorer DT performance. Now that there is an increased level of certainty surrounding an association between concussion and subsequent injury, future research needs to shift to begin investigating prevention strategies. Injury prevention programs have been successful in lowering the risk of subsequent injury in individuals with ACL injury, as neuromuscular control deficiencies are a known risk factor of secondary ACL injury.[267] These programs target specific movement strategies with correct execution requirements and goals set at each stage of the program.[267] As our results demonstrated an increased risk of injury specifically in the lower extremity, it is possible that targeting specific exercises to work on neuromuscular control of these areas may lower subsequent injury risk. Athletic healthcare providers can work with strength and conditioning staffs to specifically target injury prevention strategies in those with elevated risks to potentially reduce the subsequent injury rate.

Our results are not without limitations. There was a change to the electronic medical records software after the study was initiated; therefore, the only athletes who were eligible for inclusion in the study were those who sustained a concussion after the software change, had a full year of injury data prior to their concussion, and had a full year after RTP to examine subsequent injury. As a result, our sample size herein (n= 64) was smaller than other collegiate student-athlete studies (102-335 participants);[98,100,105] however, we also incorporated gait at both baseline and RTP, which made for a more stringent participant inclusion criteria. We were reliant on team athletic trainers to input injury data into the SWOL software, and there were multiple cases of no data entry to athletes on given days. Despite these limitations, we were still able to add to the growing evidence of a concussion-subsequent injury association.

There is an emerging scientific consensus indicating a 1.5 – 2.5x elevated risk of subsequent lower extremity musculoskeletal injury in the year following concussion and the results herein support these findings. Our study found a 1.82x increased risk of acute lower extremity injury in the concussion group, compared to controls. Further, we were able to identify distinct differences in gait parameters between the injury and non-injury groups. Thus, now that a risk factor for subsequent injury has been identified, future research can begin to focus on strategies to lower the number of injuries that occur following concussion.

REFERENCES

1. McCrory PR, Berkovic SF. Concussion: the history of clinical and pathophysiological concepts and misconceptions. *Neurology*. 2001;57:2283-2289.
2. McCrory P, Meeuwisse WH, Aubry M, et al. Consensus statement on concussion in sport: the 4th International Conference on Concussion in Sport held in Zurich, November 2012. *Br J Sports Med*. 2013;47(5):250-258.
3. Langlois J a, Rutland-Brown W, Wald MM. The epidemiology and impact of traumatic brain injury: a brief overview. *J Head Trauma Rehabil*. 2006;21(5):375-378.
4. Zuckerman SL, Kerr ZY, Yengo-Kahn A, Wasserman E, Covassin T, Solomon GS. Epidemiology of Sports-Related Concussion in NCAA Athletes From 2009-2010 to 2013-2014: Incidence, Recurrence, and Mechanisms. *Am J Sports Med*. 2015.
5. Marar M, McIlvain NM, Fields SK, Comstock RD. Epidemiology of Concussions Among United States High School Athletes in 20 Sports. *Am J Sports Med*. 2012;40(4):747-755.
6. Bakhos LL, Lockhart GR, Myers R, Linakis JG. Emergency department visits for concussion in young child athletes. *Pediatrics*. 2010;126(3):e550-e556.
7. Hunt T, Ferrara M. Age-related differences in neuropsychological testing among high school athletes. *J Athl Train*. 2009;44:405-409.
8. Fischer K, Rose S. Dynamic growth cycles of brain and cognitive development.

In: *Developmental Neuroimaging*. ; 197AD:263-279.

9. Guskiewicz K, Valovich McLeod T. Pediatric Sports-related Concussion. *PM R*. 2011;3:353-364.

10. Field M, Collins MW, Lovell MR, Maroon J. Does age play a role in recovery from sports-related concussion? A comparison of high school and collegiate athletes. *J Pediatr*. 2003;142(5):546-553.

11. Moser RS, Schatz P, Jordan BD. Prolonged effects of concussion in high school athletes. *Neurosurgery*. 2005;57(2):300-306.

12. Sim A, Terryberry-Spohr L, WIlson K. Prolonged recovery of memory functioning after mild traumatic brain injury in adolescent athletes. *J Neurosurg*. 2008;108:511-516.

13. McCrea M, Guskiewicz KM, Marshall SW, et al. Acute effects and recovery time following concussion in collegiate football players: the NCAA concussion study. *JAMA*. 2003;290(19):2556-2563.

14. Prins M, Hovda D. Developing experimental models to address traumatic brain injury in children. *J Neurotrauma*. 2003;20:123-137.

15. Thibault K, Margulies S. Age-dependent material properties of the porcine cerebrum: effect on pediatric inertial head injury criteria. *J Biomech*. 1998;31:1119-1126.

16. Zwienenberg M, Muizelaar J. Cerebral perfusion and blood flow in neurotrauma. *Neurol Res*. 2001;23:167-174.

17. Zwienenberg M, Muizelaar J. Severe pediatric head injury: the role of

hyperemia revisited. *J Neurotrauma*. 1999;16:937-943.

18. Goldsmith W, Plunkett J. A biomechanical analysis of the causes of traumatic brain injury in infants and children. *Am J Forensic Med Pathol*. 2004;25:89-100.

19. J.M. Hootman, R. Dick JA. Epidemiology of collegiate injuries for 15 sports: summary and recommendations for injury prevention initiatives. *J Athl Train*. 2007;42(2):311-319.

20. Tierney R, Sitler M, Swanik C, Swanik K, Higgins M, Torg J. Gender Differences in Head-Neck Segment Dynamic Stabilization during Head Acceleration. *Med Sci Sport Exerc*. 2005;37(2):272-279.

21. Barnes BC, Cooper L, Kirkendall DT, McDermott TP, Jordan BD, Garrett Jr. WE. Concussion history in elite male and female soccer players. *Am J Sport Med*. 1998;26(3):433-438.

22. Mansell J, Tierney RT, Sitler MR, Swanik K a, Stearne D. Resistance training and head-neck segment dynamic stabilization in male and female collegiate soccer players. *J Athl Train*. 2005;40(4):310-319.

23. Zuckerman SL, Lee YM, Odom MJ, Forbes JA, Solomon GS, Sills AK. Sports-Related Concussion in Helmeted vs. Unhelmeted Athletes: Who Fares Worse? *Int J Sports Med*. 2015.

24. Dick R, Putukian M, Agel J, Evans T a, Marshall SW. Descriptive Epidemiology of Collegiate Women ' s Soccer Injuries : National Collegiate Athletic Association Injury Surveillance System , 1988 – 1989 Through 2002 –

2003. *J Athl Train*. 2007;42(2):278-285.

25. Llewellyn T, Burdette GT, Joyner a B, Buckley T a. Concussion reporting rates at the conclusion of an intercollegiate athletic career. *Clin J Sport Med*. 2014;24(1):76-79.

26. Torres DM, Galetta KM, Phillips HW, et al. Sports-related concussion: Anonymous survey of a collegiate cohort. *Neurol Clin Pract*. 2013;3(4):279-287.

27. Giza CC, Hovda DA. The Neurometabolic Cascade of Concussion. *J Athl Train*. 2001;36(3):228-235.

28. Giza CC, Hovda DA. The New Neurometabolic Cascade of Concussion. *Neurosurgery*. 2014;75(4):S24-S33.

29. McCrory P, Meeuwisse W, Dvorak J, et al. Consensus statement on concussion ins sport-the 5th international conference on concussion in sport held in Berlin, October 2016. *Br J Sport Med*. 2017:51(11):838-47.

30. Maddocks DL, Dicker GD, Saling M. The Assessment of Orientation Following Concussion in Athletes. *Clin J Sport Med*. 1995;5:32-35.

31. Guskiewicz KM, Weaver NL, Padua D a, Garrett WE. Epidemiology of Concussion in Collegiate and High School Football Players. *Am J Sport Med*. 2000;28(5):643-650.

32. Guskiewicz KM, Mccrea M, Marshall SW, et al. Cumulative Effects Associated With Recurrent Concussion in Collegiate Football Players: The NCAA Concussion Study. *JAMA*. 2003;290(19):2549-2555.

33. McCrea M, Guskiewicz KM, Marshall SW, et al. Acute effects and recovery time following concussion in collegiate football players: the NCAA Concussion Study. *Jama*. 2003;290(19):2556-2563.

34. McCrea M, Barr WB, Guskiewicz K, et al. Standard regression-based methods for measuring recovery after sport-related concussion. *J Int Neuropsychol Soc*. 2005;11(1):58-69.

35. Willer B, Leddy JJ. Management of concussion and post-concussion syndrome. *Curr Treat Options Neurol*. 2006;8(5):415-426.

36. Lau B, Kontos A, Collins M, Mucha A, Lovell M. Which On-field Signs/Symptoms Predict Protracted Recovery from Sport-Related Concussion Among High School Football Players? *Am J Sports Med*. 2011;39(11):2311-2318.

37. M.W. Collins, G.L. Iverson, M.R. Lovell et al. On-Field Predictors of Neuropsychological and Symptom Deficit Following Sports-related Concussion. *Clin J Sport Med*. 2003;13:222-229.

38. McCrea M, Guskiewicz K, Randolph C, et al. Incidence, Clinical Course, and Predictors of Prolonged Recovery Time Following Sport-Related Concussion in High School and College Athletes. *J Int Neuropsychol Soc*. 2013;19(1):22-33.

39. McCrea M, Hammeke T, Olsen G, Leo P, Guskiewicz K. Unreported concussion in high school football players: implications for prevention. *Clin J Sport Med*. 2004;14(1):13-17.

40. Chrisman SP, Quitiquit C, Rivara FP. Qualitative Study of Barriers to

Concussive Symptom Reporting in High School Athletics. *J Adolesc Heal*. 2013;52(3):330-335.

41. Guskiewicz K, Marshall S, Bailes J, et al. Association between recurrent concussion and late-life cognitive impairment in retired professional football players. *Neurosurgery*. 2005;57(4):719-726.

42. Covassin T, Stearne D, Elbin R. Concussion history and postconcussion neurocognitive performance and symptoms in collegiate athletes. *J Athl Train*. 2008;43(2):119-124.

43. Iverson GL, Gaetz M, Lovell MR, Collins MW. Cumulative effects of concussion in amateur athletes. *Brain Inj*. 2004;18(5):433-443.

44. Iverson G, Brooks B, Lovell M, Collins M. No cumulative effects for one or two previous concussions. *Br J Sport Med*. 2006;40:72-75.

45. Brooks BL, Mrazik M, Barlow KM, McKay CD, Meeuwisse WH, Emery C a. Absence of differences between male and female adolescents with prior sport concussion. *J Head Trauma Rehabil*. 2014;29(3):257-264.

46. Brooks B, McKay C, Mrazik M, Barlow K, Meeuwisse W, Emery C. Subjective, but not objective, lingering effects of multiple past concussions in adolescents. *J Neurotrauma*. 2013;29:257-264.

47. Broglio S, Ferrara M, Piland S, Anderson R, Collie A. Concussion history is not a predictor of computerised neurocognitive performance. *J Sport Med*. 2006;40:802-805.

48. Martini D, Sabin M, DePesa S, et al. The chronic effects of concussion on gait.

Arch Phys Med Rehabil. 2011;92:585-589.

49. Sosnoff JJ, Broglio SP, Shin S, Ferrara MS, Fnata À. Previous Mild Traumatic Brain Injury and Postural- Control Dynamics. 2011;46(1):85-91.

50. Buckley TA, Vallabhajosula S, Oldham JR, et al. Evidence of a conservative gait strategy in athletes with a history of concussions. *J Sport Heal Sci*. 2016;5(4): 417-23.

51. Buckley TA, Oldham JR, Caccese JB. Postural control deficits identify lingering post-concussion neurological deficits. *J Sport Heal Sci*. 2016;5(1): 61-9.

52. Bowen AP. Second impact syndrome: A rare, catastrophic, preventable complication of concussion in young athletes. *J Emerg Nurs*. 2003;29(3):287-289.

53. Guskiewicz KM, Marshall SW, Bailes J, et al. Recurrent Concussion and Risk of Depression in Retired Professional Football Players. *Med Sci Sports Exerc.* 2007;39(6):903-909.

54. Martland HS. Punch Drunk. *JAMA*. 1928;91(15):1103-1107.

55. Bower, JH Maraganore, DM Peterson, BJ McDonnell, SK Ahiskog, JE Rocca W. Head trauma preceding PD: a case-control study. *Neurology*. 2003;60(10):1610-1615.

56. Mortimer, JA van Duijn, CM Chandra, V Fratiglioni L, Graves, AB Heyman, A Jorm, AF Kokmen, E Kondo, K Rocca W. Head trauma as a risk factor for Alzheimer's disease: a collaborative re-analysis of case-control studies.

EURODEM Risk Factors Research Group. *Int J Epidemiol*. 1991;20(Suppl 2):S28-35.

57. A. Chio, G. Benzi, M. Dossena, R. Mutani GM. Severely increased risk of amyotrophic lateral sclerosis among Italian professional football players. *Brain*. 2005;128:472-476.

58. Randolph C, Karantzoulis S, Guskiewicz K. Prevalence and characterization of mild cognitive impairment in retired national football league players. *J Int Neuropsychol Soc*. 2013;19:873-880.

59. Savica R, Parisi JE, Wold LE, Josephs K a., Ahlskog JE. High school football and risk of neurodegeneration: A community-based study. *Mayo Clin Proc*. 2012;87(4):335-340.

60. Gavett BE, Stern RA, McKee AC, et al. Chronic traumatic encephalopathy: a potential late effect of sport-related concussive and subconcussive head trauma. *Clin Sports Med*. 2011;30(1):179-188.

61. McKee AC, Stein TD, Nowinski CJ, et al. The spectrum of disease in chronic traumatic encephalopathy. *Brain*. 2013;136(1):43-64.

62. McKee AC, Cantu RC, Nowinski CJ, et al. Chronic Traumatic Encephalopathy in Athletes: Progressive Tauopathy following Repetitive Head Injury. *J Neuropathol Exp Neurol*. 2009;68(7):709-735.

63. Iverson GL. Chronic traumatic encephalopathy and risk of suicide in former athletes. *Br J Sport Med*. 2014;48(2):162-164.

64. Gysland SM, Mihalik JP, Register-Mihalik JK, Trulock SC, Shields EW,

Guskiewicz KM. The relationship between subconcussive impacts and concussion history on clinical measures of neurologic function in collegiate football players. *Ann Biomed Eng*. 2012;40(1):14-22.

65. Broglio S, Eckner J, Martini D, Sosnoff J, Kutcher J, Randolph C. Cumulative head impact burden in high school football. *J Neurotrauma*. 2011;28(10):2069-2078.

66. Mcallister TW, Maerlender A, Beckwith JG, Crisco JJ. Cognitive effects of one season of head impacts in a cohort of collegiate contact sport athletes. *Neurology*. 2012;79(4):393-393.

67. Broglio SP, Macciocchi SN, Ferrara MS. Sensitivity of the Concussion Assessment Battery. *Neurosurgery*. 2007;60(6):1050-1058.

68. Lovell MR, Collins M. Neuropsychological assessment of the college football player. *J Head Trauma Rehabil*. 1998;13:9-26.

69. Guskiewicz KM, Ross SE, Marshall SW. Postural Stability and Neuropsychological Deficits After Concussion in Collegiate Athletes. *J Athl Train*. 2001;36(3):263-273.

70. Finnoff JT, Peterson VJ, Hollman JH, Smith J. Intrarater and Interrater Reliability of the Balance Error Scoring System (BESS). *Pm&R*. 2009;1(1):50-54.

71. Rahn C, Munkasy B, Joyner B, Buckley T. Sideline Performance of the Balance Error Scoring System during a Live Sporting Event. *Clin J Sport Med*. 2015;25(3):248-253.

72. Valovich TC, Perrin DH, Gansneder BM. Repeat administration elicits a practice effect with the Balance Error Scoring System but not with the Standardized Assessment of Concussion in high school athletes. *J Athl Train*. 2003;38(1):51-56.

73. McCrea M. Standardized Mental Status Testing on the Sideline after Sport-Related Concussion. *J Athl Train*. 2001;36(3):274-279.

74. McCrea M, Kelly JP, Randolph C, et al. Immediate neurocognitive effects of concussion. *Neurosurgery*. 2002;50(5):1032-1042.

75. Lovell MR, Collins MW, Iverson GL, et al. Recovery from mild concussion in high school athletes. *J Neurosurg*. 2003;98:295-301.

76. Resch J, Driscoll A, McCaffrey N, et al. ImPact test-retest reliability: reliably unreliable? *J Athl Train*. 2013;48(4):506-511.

77. Marinides Z, Galetta K. Vision testing is additive to the sideline assessment of sports-related concussion. *Neurology: Clinical Practice.*2014:1-10.

78. Heitger MH, Jones RD, MacLeod a. D, Snell DL, Frampton CM, Anderson TJ. Impaired eye movements in post-concussion syndrome indicate suboptimal brain function beyond the influence of depression, malingering or intellectual ability. *Brain*. 2009;132:2850-2870.

79. Galetta KM, Barrett J, Allen M, et al. The King-Devick test as a determinant of head trauma and concussion in boxers and MMA fighters. *Neurology*. 2011;76(17):1456-1462.

80. Galetta KM, Brandes LE, Maki K, et al. The King-Devick test and sports-

related concussion: study of a rapid visual screening tool in a collegiate cohort. *J Neurol Sci*. 2011;309(1-2):34-39.

81. Galetta MS, Galetta KM, McCrossin J, et al. Saccades and memory: Baseline associations of the King–Devick and SCAT2 SAC tests in professional ice hockey players. *J Neurol Sci*. 2013;328(1-2):28-31.

82. Silverberg ND, Iverson GL. Is Rest After Concussion "The Best Medicine?" *J Head Trauma Rehabil*. 2013;28(4):250-9.

83. Allen C, Glasziou P, Del Mar C. Bed rest: A potentially harmful treatment needing more careful evaluation. *Lancet*. 1999;354(9186):1229-1233.

84. Berlin AA, Kop WJ, Deuster PA. Depressive Mood Symptoms and Fatigue After Exercise Withdrawal: The Potential Role of Decreased Fitness. *Psychosom Med*. 2006;68(2):224-230.

85. Buckley TA, Munkasy BA, Clouse BP. Acute Cognitive and Physical Rest May Not Improve Concussion Recovery Time. *J Head Trauma Rehabil*. 2016; 31(4): 233-41.

86. Thomas DG, Apps JN, Hoffmann RG, McCrea M, Hammeke T. Benefits of Strict Rest After Acute Concussion: A Randomized Controlled Trial. *Pediatrics*. 2015;135(2):213-223.

87. Majerske CW, Mihalik JP, Ren D, et al. Concussion in sports: Postconcussive activity levels, symptoms, and neurocognitive performance. *J Athl Train*. 2008;43(3):265-274.

88. Gibson S, Nigrovic LE, O'Brien M, Meehan WP. The effect of recommending

cognitive rest on recovery from sport-related concussion. *Brain Inj*. 2013;27(7-8):839-842.

89. Gall B. Exercise following a sport induced concussion. *Br J Sports Med*. 2004;38(6):773-777.

90. Schneiders AG, Sullivan SJ, McCrory PR, et al. The effect of exercise on motor performance tasks used in the neurological assessment of sports-related concussion. *Br J Sports Med*. 2008;42(12):1011-1013.

91. Schneiders AG, Sullivan SJ, Handcock P, Gray A, McCrory PR. Sports concussion assessment: the effect of exercise on dynamic and static balance. *Scand J Med Sci Sports*. 2012;22(1):85-90.

92. Leddy JJ, Kozlowski K, Fung M, Pendergast DR, Willer B. Regulatory and autoregulatory physiological dysfunction as a primary characteristic of post concussion syndrome: implications for treatment. *NeuroRehabilitation*. 2007;22(3):199-205.

93. Griesbach GS. Exercise After Traumatic Brain Injury: Is it a Double-Edged Sword? *Pm&R*. 2011;3(6):S64-S72.

94. Baker JG, Freitas MS, Leddy JJ, Kozlowski KF, Willer BS. Return to Full Functioning after Graded Exercise Assessment and Progressive Exercise Treatment of Postconcussion Syndrome. *Rehabil Res Pract*. 2012;2012:1-7.

95. Alla S, Sullivan SJ, McCrory P, Schneiders AG, Handcock P. Does exercise evoke neurological symptoms in healthy subjects? *J Sci Med Sport*. 2010;13(1):24-26.

96. Covassin T, Weiss L, Powell J, Womack C, Lovell MR. Effects of a maximal exercise test on neurocognitive function. *Br J Sports Med*. 2007;41(6):370-374.

97. Makdissi M, McCrory P, Ugoni A, Darby D, Brukner P. A Prospective Study of Postconcussive Outcomes After Return to Play in Australian Football. *Am J Sports Med*. 2009;37(5):877-883.

98. Brooks M, Peterson K, Biese K. Concussion increases odds of sustaining a lower extremity musculoskeletal injury after return to play among collegiate athletes. *Am J Sport Med*. 2016;44:742-747.

99. Cross M, Kemp S, Smith A. Professional Rugby Union players have a 60% greater risk of time loss injury after concussion: a 2-season prospective study of clinical outcomes. *Br J Sport Med*. 2016;50:926-931.

100. Lynall RC, Mauntel TC, Padua D a., Mihalik JP. Acute Lower Extremity Injury Rates Increase following Concussion in College Athletes. *Med Sci Sport Exerc*. 2015;47(12):2487-2492.

101. Nordstrom A, Nordstrom P, Ekstrand J. Sports-related concussion increases the risk of subsequent injury by about 50% in elite male football players. *Br J Sports Med*. 2014;48(19):1447-1450.

102. Burman E, Lysholm J, Shahim P. Concussed athletes are more prone to injury both before and after their index concussion: a data base analysis of 699 concussed contact sports athletes. *BMJ Open Sport Exerc Med*. 2016;2:e000092.

103. Pietrosimone B, Golightly Y, Mihalik J, Guskiewicz K. Concussion frequency

associates with musculoskeletal injury in retired NFL players. *Med Sci Sport Exerc*. 2015;47(11):2366-2372.

104. Nyberg G, Mossbeeg K, Lysholm J, Tegner Y. Subsequent traumatic injuries after a concussion in elite ice hockey: a study over 28 years. *Curr Res Concussion*. 2015;2(3):109-112.

105. Herman D, Jones D, Harrison A. Concussion may increase the risk of subsequent lower extremity musculoskeletal injury in collegiate athletes. *Sport Med*. 2017;47:1003-1010.

106. Gilbert F, Burdette G, Joyner A. Association between concussion and lower extremity injuries in collegiate athletes. *Sports Health*. 2016;8:561-567.

107. Howell D, Lynall R, Buckley T, Herman D. Neuromuscular control deficits and the risk of subsequent injury after a concussion: a scoping review. *Sport Med*. 2018;[EPub]

108. Pietrosimone B, Golightly Y, Mihalik J, Guskiewicz K. Concussion frequency associates with musculoskeletal injury in retired NFL players. *Med Sci Sport Exerc*. 2015;47(11): 2366-2372.

109. Pietrosimone B, Golightly YM, Mihalik JP, et al. Concussion Frequency Associates with Musculoskeletal Injury in Retired NFL Players. *Med Sci Sport Exerc*. 2015;47(11): 2366-2372.

110. Plisky, P.J. Rauh, M.J. Kaminski, T.W. Underwood FB. Star Excursion Balance Test as a predictor of lower extremity injury in high school basketball players. *J Orthop Sport Phys Ther*. 2006;36(12):911-919.

111. Parker TM, Osternig LR, van Donkelaar P, Chou L-S. Balance control during gait in athletes and non-athletes following concussion. *Med Eng Phys*. 2008;30(8):959-967.

112. Parker T, Osternig L, Van Donkelarr P, Chou L. Gait Stability following Concussion. *Med Sci Sport Exerc*. 2006;38(6):1032-1040.

113. Norlin, R. Odenrick, P. Sandlund B. Development of gait in the normal child. *J Pediatr Orthop*. 1981;1(3):261-266.

114. Shumway-Cook A, Woollacott MH. Normal Postural Control. In: 4th Editio. Motor Control: Translating research into clinical practice. Lippincott, Williams & Wilkins; 2012:161-162.

115. Takakusaki K. Neurophysiology of Gait: From the Spinal Cord to the Frontal Lobe. *Mov Disord*. 2013;28(11):1483-1491.

116. Takakusaki K. Functional Neuroanatomy for Posture and Gait Control. *J Mov Disord*. 2017;10(1):1-17.

117. Haghpanah S, Farahmand F, Zohoor H. Modular neuromuscular control of human locomotion by central pattern generator. *J Biomech*. 2017:1-9.

118. Minassian K, Hofstoetter U, Dzeladini F, Guertin P, Ijspeert A. The Human Central Pattern Generator for Locomotion: Does It Exist and Contribute to Walking? *Neurosci*. 2017;23(6):649-663.

119. Guertin P. Central pattern generator for locomotion: anatomical, physiological, and pathophysiological considerations. *Front Neurol*. 2013;3(183):1-15.

120. Rossignol S, Lund J, Drew T. The role of sensory inputs in regulating patterns

of rhythmical movements in higher vertebrates. In: *Neural Control of Rhythmic Movements in Vertebrates*. ; 1988:201-283.

121. Wang J, Wai Y, Weng Y, et al. Functional MRI in the assessment of cortical activation during gait-related imaginary tasks. *J Neural Transm*. 2009;116:1087-1092.

122. Zhang, S. Li L. Feedforward and feedback control for gait and balance. In: *Gait Biometrics*. ; 2014:191-205.

123. Parker TM, Osternig LR, Lee H-J, Donkelaar P van, Chou L-S. The effect of divided attention on gait stability following concussion. *Clin Biomech*. 2005;20(4):389-395.

124. Catena RD, van Donkelaar P, Chou L-S. Cognitive task effects on gait stability following concussion. *Exp Brain Res*. 2007;176(1):23-31.

125. Parker TM, Osternig LR, van Donkelaar P, Chou L. Gait stability following concussion. *Med Sci Sport Exerc*. 2006;38(6):1032-1040.

126. Oldham J, Evans K, Munkasy B, Wikstrom E, Buckley T. Altered dynamic postural control during gait termination following concussion. *Gait Posture*. 2016;49:437-442.

127. Catena RD, van Donkelaar P, Chou L. Altered balance control following concussion is better detected with an attention test during gait. *Gait Posture*. 2007;25:406-411.

128. Catena RD, van Donkelaar P, Chou L. Different gait tasks distinguish immediate vs. long-term effects of concussion on balance control. *J Neuroeng*

Rehabil. 2009;6(25):1-7.

129. Catena RD, van Donkelaar P, Halterman CI, Chou L-S. Spatial orientation of attention and obstacle avoidance following concussion. *Exp Brain Res*. 2009;194(1):67-77.

130. Catena RD, van Donkelaar P, Chou L-S. The effects of attention capacity on dynamic balance control following concussion. *J Neuroeng Rehabil*. 2011;8(1):8.

131. Parker TM, Osternig LR, Lee H, van Donkelaar P, Chou L. The effect of divided attention on gait stability folllowing concussion. *Clin Biomech*. 2005;20:389-395.

132. Buckley TA, Munkasy BA, Tapia-Lovler TG, Wikstrom EA. Altered gait termination strategies following a concussion. *Gait Posture*. 2013;38:549-551.

133. Howell DR, Osternig LR, Koester MC, Chou L-S. The effect of cognitive task complexity on gait stability in adolescents following concussion. *Exp Brain Res*. 2014;232(6):1773-1782.

134. Howell D, Osternig L, Chou L. Monitoring recovery of gait balance control following concussion using an accelerometer. *J Biomech*. 2015;48(12):3364-3368.

135. Perry J. *Gait Analysis Normal and Pathological Function*. Thorofare, NJ: SLACK Incorporated; 1992.

136. Catena RD, van Donkelaar P, Chou L-S. Altered balance control following concussion is better detected with an attention test during gait. *Gait Posture*.

2007;25(3):406-411.

137. Catena RD, van Donkelaar P, Chou L-S. Different gait tasks distinguish immediate vs. long-term effects of concussion on balance control. *J Neuroeng Rehabil*. 2009;6(1):25.

138. Buckley TA, Munkasy BA, Tapia-Lovler TG, Wikstrom EA. Altered gait termination strategies following a concussion. *Gait Posture*. 2013;38(3):549-551.

139. Halliday S, Winter D, Frank J, Patla A, Prince F. The initiation of gait in young, elderly, and Parkinson's disease subjects. *Gait Posture*. 1998;8:8-14.

140. Buckley T, Oldham J, Munkasy B, Evans K. Decreased anticipatory postural adjustments during gait initiation acutely post-concussion. *Arch Phys Med Rehabil*. 2017;98(10): 1962-1968.

141. Massion J. Movement, Posture and Equilibrium: Interaction and Coordination. *Prog Neurobiol*. 1992;38:35-56.

142. Chang W, Tang P, Wang Y, Lin K, Chiu M, Chen S. Role of the premotor cortex in leg selection and anticipatory postural adjustments associated with a rapid stepping task in patients with stroke. *Gait Posture*. 2010;32:487-493.

143. Howell D, Osternig L, Chou L-S. Monitoring recovery of gait balance control following concussion using an accelerometer. *J Biomech*. 2015;48(12):3364-3368.

144. Mancini M, Chiari L, Holmstrom L, Salarian A, Horak F. Validitiy and reliability of an IMU-based method to detect APAs prior to gait initiation. *Gait*

Posture. 2016;43:125-131.

145. Horak F, Mancini M. Objective biomarkers of balance and gait for Parkinson's disease using body-worn sensors. *Mov Disord*. 2013;28:1544-1551.

146. Maetzler W, Domingos J, Srulijes K, Kerreira J, Bloem B. Quantitative wearable sensors for objective assessment of Parkinson's disease. *Mov Disord*. 2013;28:1628-1637.

147. Yang S, Li Q. Inertial sensor-based methods in walking speed estimation: a systematic review. *Sensors*. 2012;12(5):6102-6116.

148. Mancini M, Carlson-Kuhta P, Zampieri C, Nutt J, Chiari L, Horak F. Postural sway as a marker of progression in Parkinson's disease: a pilot longitudinal study. *Gait Posture*. 2012;36(3):471-476.

149. Mancini M, Zampieri C, Carlson-Kuhta P, Chiari L, Horak F. Anticipatory postural adjustments prior to step initiation are hypometric in untreated Parkinson's disease: an accelerometer-based approach. *Eur J Neurol*. 2009;16(9):1028-1034.

150. Bonora G, Mancini M, Carpinella I, Chiari L, Horak F, Ferrarin M. Gait initiation is impaired in subjects with Parkinson's disease in the OFF state: Evidence from the analysis of the anticipatory postural adjustments through wearable inertial sensors. *Gait Posture*. 2017;51:218-221.

151. King L, Horak F, Mancini M, et al. Instrumenting the balance error scoring system for use with patients reporting persistent balance problems after mild traumatic brain injury. *Arch Phys Med Rehabil*. 2014;95(2):353-359.

152. Howell D, Oldham J, DiFabio M, et al. Single-task and dual-task gait among collegiate athletes of different sport classifications: implications for concussion management. *J Appl Biomech*. 2017;33(1): 24-31.

153. Mancini M, Salarian A, Carlson-Kuhta P, et al. ISway: a sensitive, valid and reliable measure of postural control. *J Neuroeng Rehabil*. 2012;9(59).

154. Mancini M, King L, Salarian A, Holmstron L, McNames J, Horak F. Mobility Lab to Assess Balance and Gait with Synchronized Body-worn Sensors. *J Bioeng Biomed Sci*. 2012;S1:007:1-5.

155. Howell D, Beasley M, Vopat L, Meehan W. The effect of prior concussion history on dual-task gait following a concussion. *J Neurotrauma*. 2017;51:A32-A33.

156. Schneiders AG, Sullivan SJ, Gray AR, Hammond-Tooke GD, McCrory PR. Normative values for three clinical measures of motor performance used in the neurological assessment of sports concussion. *J Sci Med Sport*. 2010;13(2):196-201.

157. M.M. Giorgetti, B.A. Harris AJ. Reliability of clinical balance outcome measures in the elderly. *Physiother Res Int*. 1998;3(4):274-283.

158. A.S. Kammerlind, P.B. Larsson, T.E.A. Ledin EIBS. Reliability of clinical balance tests and subjective ratings in dizziness and disequilibrium. *Adv Physiother*. 2005;7:96-107.

159. SCAT3. *Br J Sports Med*. 2013;47:259-263.

160. Echemendia RJ, Meeuwisse W, McCrory P, et al. The Sport Concussion

Assessment Tool 5th Edition (SCAT5). *Br J Sport Med*. 2017;51(11):848-850.

161. Cohen HS, Mulavara AP, Peters BT, Sangi-Haghpeykar H, Bloomberg JJ. Tests of walking balance for screening vestibular disorders. *J Vestib Res Equilib Orientat*. 2012;22(2-3):95-104.

162. Nelson L, Loman M, LaRoche A, Furger R, McCrea M. Baseline performance and psychometric properties of the child sport concussion assessment tool 3 in 5 to 13 year old athletes. *Clin J Sport Med*. 2017;27(4):381-387.

163. Oldham J, DiFabio M, Kaminski T, DeWolf R, Buckley T. Normative tandem gait in collegiate student-athletes: implications for clinical concussion assessment. *Sport Heal A Multidiscip Approach*. 2017;9(4):305-311.

164. Hanninen T, Tuominen M, Parkkari J, et al. Sport concussion assessment tool-3rd edition- normative reference values for professional ice hockey players. *J Sci Med Sport*. 2016;19(8):636-641.

165. Oldham J, DiFabio M, Kaminski T, DeWolf R, Howell D, Buckley T. Efficacy of Tandem Gait to Identify Impaired Postural Control Following Concussion. *Med Sci Sport Exerc*. 2018.[EPub]

166. Howell D, Osternig L, Chou L. Single-task and dual-task tandem gait test performance after concussion. *J Sci Med Sport*. 2017;20(7):622-626.

167. Langlois JA, Rutland-Brown W, Wald MM. The epidemiology and impact of traumatic brain injury- A brief overview. *J Head Trauma Rehabil*. 2006;21(5):375-378.

168. Gerberding JL BS. Report to Congress on Mild Traumatic Brain Injury in the

United States: Steps to prevent a serious public health problem. *Centers Dis Control Prev*. 2003.

169. Cantu R. Second-impact syndrome. *Clin Sport Med*. 1998;17(1):37-44.

170. Boden BP, Tacchetti RL, Cantu RC, Knowles SB, Mueller FO. Catastrophic Head Injuries in High School and College Football Players. *Am J Sports Med*. 2007;35(7):1075-1081.

171. Bey T, Ostick B. Second impact syndrome. *West J Emerg Med*. 2009;10(1):6-10.

172. Collins MW, Lovell MR, Iverson GL, Cantu RC, Maroon JC, Field M. Cumulative effects of concussion in high school athletes. *Neurosurgery*. 2002;51(5):1171-1175.

173. Castile L, Collins C, McIlvain N, Comstock R. The epidemiology of new versus recurrent sports concussions among high school athletes, 2005-2010. *Br J Sports Med*. 2012;46(8):603-610.

174. Zemper ED. Two-year prospective study of relative risk of a second cerebral concussion. *Am J Phys Med Rehabil*. 2003;82(9):653-659.

175. McKee AC, Gavett BE, Stern RA, et al. TDP-43 proteinopathy and motor neuron disease in chronic traumatic encephalopathy. *J Neuropathol Exp Neurol*. 2010;69(9):918-929.

176. Broglio SP, Cantu RC, Gioia GA, Guskiewicz KM, Kutcher J, Palm M. National Athletic Trainers' Association position statement: Management of sport concussion. *J Athl Train*. 2014;49(2):245-265.

177. Giza CC, Kutcher JS, Ashwal S, et al. Summary of evidence-based guideline update: Evaluation and management of concussion in sports: Report of the Guideline Development Subcommittee of the American Academy of Neurology. *Neurology*. 2013;80(24):2250-2257.

178. McCrea M, Barr WB, Guskiewicz K, et al. Standard regression-based methods for measuring recovery after sport-related concussion. *J Int Neuropsychol Soc*. 2005;11(1):58-69.

179. Riemann BL, Guskiewicz KM, Shields EW. Relationship between clinical and forceplate measures of postural stability. *J Sport Rehabil*. 1999;8(2):71-82.

180. Finnoff JT, Peterson VJ, Hollman JH, Smith J. Intrarater and interrater reliability of the balance error scoring system (BESS). *PM&R*. 2009;1(1):50-54.

181. Valovich McLeod T, Barr WB, McCrea M, Guskiewicz KM. Psychometric and measurement properties of concussion assessment tools in youth sports. *J Athl Train*. 2006;41(4):399-408.

182. Norlin R, Odenrick P, Sandlund B. Development of gait in the normal child. *J Pediatr Orthop*. 1981;1(3):261-266.

183. Chang H, Krebs D. Dynamic balance control in elders: gait initiation assessment as a screening tool. *Arch Phys Med Rehabil*. 1999;80(5):490-494.

184. Hass C, Gregor R, Waddell D, et al. The influence of tai chi training on the center of pressure trajectory during gait initiation in older adults. *Arch Phys Med Rehabil*. 2004;85:1593-1598.

185. Hass C, Waddell D, Wolf S, Juncos J, Gregor R. Gait initiation in older adults

with postural instability. *Clin Biomech*. 2008;23(6):743-753.

186. Hass CJ, Buckley TA, Pitsikoulis C, Barthelemy EJ. Progressive resistance training improves gait initiation in individuals with Parkinson's disease. *Gait Posture*. 2012;35(4):669-673.

187. Vallabhajosula S, Buckley T, Tillman M, Hass C. Age and Parkinson's disease related kinematic alterations during multidirectional gait initiation. *Gait Posture*. 2013;37:280-286.

188. Howell D, Osternig L, Chou L. Dual-task effect on gait balance control in adolescents with concussion. *Arch Phys Med Rehabil*. 2013;94(8):1513-1520.

189. Howell DR, Osternig LR, Chou L-S. Adolescents Demonstrate Greater Gait Balance Control Deficits After Concussion Than Young Adults. *Am J Sports Med*. 2015;43(3):625-632.

190. Woollacott M, Shumway-Cook A. Attention and the control of posture and gait: a review of an emerging area of research. *Gait Posture*. 2002;16:1-14.

191. Kerr B, Condon S, McDonald L. Cognitive spatial processing and the regulation of posture. *J Exp Psychol*. 1985;11:617-622.

192. Pashler H. Dual-task interference in simple tasks: data and theory. *Psychol Bull*. 1994;116(2):220-244.

193. Broglio SP, Puetz TW. The effect of sport concussion on neurocognitive function, self-report symptoms and postural control : a meta-analysis. *Sport Med*. 2008;38(1):53-67.

194. Howell D, Osternig L, Chou L. Return to activity after concussion affects dual-

task gait balance control recovery. *Med Sci Sports Exerc.* 2015; 47(4): 673-680.

195. Horak F, King L, Mancini M. Role of body-worn movement monitor technology for balance and gait rehabilitation. *Phys Ther*. 2015;95(3):461-470.

196. *APDM Mobility Lab User's Guide*.; 2014.

197. Salarian A, Horak F, Zampieri C, Nutt J, Carlson-Kuhta P, Aminian K. iTUG, a sensitive and reliable measure of mobility. *IEEE Trans Neural Syst Rehabil Eng*. 2010;18(3):303-310.

198. Buckley TA, Oldham JR, Munkasy BA, Evans KM. Decreased Anticipatory Postural Adjustments During Gait Initiation Acutely Postconcussion. *Arch Phys Med Rehabil*. 2017.

199. Jantzen K, Anderson B, Steinberg F, Kelso J. A prospective functional MR imaging study of mild traumatic brain injury in college football players. *Am J Neuroradiol*. 2004;25:738-745.

200. Slobounov S, Sebastianelli W, Moss R. Alteration of posture-related cortical potentials in mild traumatic brain injury. *Neurosci Lett*. 2005;383(3):251-255.

201. Henry L, Tremblay S, Boulanger Y, Ellemberg D, Lassonde M. Neurometabolic changes in the acute phase after sports concussions correlate with symptom severity. *J Neurotrauma*. 2010;27:65-76.

202. Chen J, Johnston K, Petrides M, Ptitio A. Neural substrates of symptoms of depression following concussion in male athletes with persisting postconcussion symptoms. *Arch Gen Psychiatry*. 2008;65:81-89.

203. Fino P, Parrington L, Pitt W, et al. Detecting gait abnormalities after concussion

or mild traumatic brain injury: a systematic review of single-task, dual-task, and complex gait. *Gait Posture*. 2018;[EPub]

204. Parker TM, Osternig LR, van Donkelaar P, Chou L. Recovery of cognitive and dynamic motor function following concussion. *Br J Sport Med*. 2007;41:868-873.

205. Chiu S-L, Osternig L, Chou L-S. Concussion induces gait inter-joint coordination variability under conditions of divided attention and obstacle crossing. *Gait Posture*. 2013;38(4):717-722.

206. Chen H-L, Lu T-W, Chou L-S. Effect of Concussion on Inter-joint Coordination During Divided-Attention Gait. *J Med Biol Eng*. 2015;35(1):28-33.

207. Howell D, Stracciolini A, Geminiani E, Meehan W. Dual-task gait differences in female and male adolescents following sport-related concussion. *Gait Posture*. 2017;54:284-289.

208. Mancini M, Horak F. The relevance of clinical balance assessment tools to differentiate balance deficits. *Eur J Phys Rehabil Med*. 2010;46(2):239-248.

209. Salarian A, Horak F, Zampieri C, Carlson-Kuhta P, Nutt J, Aminian K. Itug, a sensitive and reliable measure of mobility. *IEEE Trans Neural Syst Rehabil Eng*. 2010;18(3):303-310.

210. Doherty C, Zhao L, Ryan J, Komaba Y, Inomata A, Caulfield B. Concussion is associated with altered prepatory postural adjustments during gait initiation. *Hum Mov Sci*. 2017;52:160-169.

211. Slobounov S, Sebastianelli W, Moss R. Alteration of posture-related corical potentials in mild traumatic brain injury. *Neurosci Let*. 2006;383:251-255.

212. Hamacher D, Herold F, Wiegel P, Hamacher D, Schega L. Brain activity during walking: A systematic review. *Neurosci Biobehav Rev*. 2015;57:310-327.

213. Sanctis P, Butler J, Malcolm B, Foxe J. Recalibration of inhibitory control systems during walking-related dual-task interference: A Mobile Brain-Body Imaging (MOBI) study. *Neuroimage*. 2014;94C:55-64.

214. Holtzer R, Mahoney J, Izzetoglu M, Izzetoglu K, Onaral B, Verghese J. fNIRS study of walking and walking while talking in young and old individuals. *J Gerontol*. 2011;66A:879-887.

215. Atsumori H, Kiguchi M, Katura T, et al. Noninvasive imaging of prefrontal activation during attention-demanding tasks performed while walking using a wearable optical topography system. *J Biomed Opt*. 2010;15.

216. Chen J, Johnston K, Frey S, Petrides M, Worsley K, Ptito A. Functional abnormalities in symptomatic concussed athletes: an fMRI study. *Neuroimage*. 2004;22:68-82.

217. Leone C, Feys P, Moumdjian L, D'Amico E, Zappia M, Patti F. Cognitive-motor dual-task interference: A systematic review of neural correlates. *Neurosci Biobehav Rev*. 2017;75:348-360.

218. Fino P, Parrington L, Walls M, et al. Abnormal turning and its association with self-reported symptoms in chronic mild traumatic brain injury. *J Neurotrauma*. 2018;[EPub]

219. Bernardin D, Kadone H, Bennequin D, Sugar T, Zaoui M, Berthoz A. Gaze anticipation during human locomotion. *Exp Brain Res*. 2012;223:65-78.

220. Mancini M, El-Gohary M, Pearson S, et al. Continuous monitoring of turning in Parkinson's disease: rehabilitation potential. *NeuroRehabilitation*. 2015;37(1):3-10.

221. SCAT3. *Br J Sports Med*. 2013;47(5):259.

222. Buckley T, Munkasy B, Clouse B. Sensitivity and specificity of the modified balance error scoring system in concussed collegiate student athletes. *Clin J Sport Med*. 2018; 28(2): 174-176.

223. Burk J, Joyner A, Munkasy B, Buckley T. Balance error scoring system performance changes after a competitive athletic season. *Clin J Sport Med*. 2013;23(4):312-317.

224. Valovich TC, Perrin DH, Gansneder BM. Repeat administration elicits a practice effect with the balance error scoring system but not with the standardized assessment of concussion in high school athletes. *J Athl Train*. 2003;38(1):51-56.

225. Docherty C, Valovich T, Shultz S. Postural control deficits in participants with functional ankle instability as measured by the balance error scoring system. *Clin J Sport Med*. 2006;16(3):203-208.

226. Fox ZG, Mihalik JP, Blackburn JT, Battaglini CL, Guskiewicz KM. Return of postural control to baseline after anaerobic and aerobic exercise protocols. *J Athl Train*. 2008;43(5):456-463.

227. Stolze H, Klebe S, Petersen G, et al. Typical features of cerebellar ataxic gait. *J Neurol Neurosurg Psychiatry*. 2002;73:310-312.

228. Giorgetti M, Harris B, Jette A. Reliability of clinical balance outcome measures in the elderly. *Physiother Res Int*. 1998;3(4):274-283.

229. Kammerlind A, Larsson P, Ledin T, Skargren E. Reliability of clinical balance tests and subjective ratings in dizziness and disequilibrium. *Adv Physiother*. 2005;7(3):96-107.

230. Shumway-Cook A, Woollacott M. *Motor Control Theory and Practical Applications*. Second Edi. (Biblis M, ed.). Lippincott Williams & Wilkins; 2001.

231. Guyton A. *Textbook of Medical Physiology*. 7th Editio. Saunders College Publishing; 1986.

232. Vander A, Sherman J, Luciano D. *Human Physiology: The Mechanisms of Body Function*. 5th Editio. New York, NY: McGraw0-Hill; 1990.

233. Howell D, Oldham J, Meehan W, DiFabio M, Buckley T. Dual-Task Tandem Gait and Average Walking Speed in Healthy Collegiate Athletes. *Clin J Sport Med*. 2017.[EPub]

234. Hanley J, McNeil B. The meaning and use of the area under a receiver operating characteristic (ROC) curve. *Radiology*. 1982;143:29-36.

235. Oldham JR, DiFabio MS, Kaminski TW, DeWolf RM, Buckley TA. Normative Tandem Gait in Collegiate Student-Athletes: Implications for Clinical Concussion Assessment. *Sports Health*. 2017;9(4): 305-311.

236. Zwergal A, Linn J, Xiong G, Brandt T, Strupp M, Jahn K. Aging of human supraspinal locomotor and postural control in fMRI. *Neurobiol Aging*. 2012;33:1073-1084.

237. La Fougere C, Zwergal A, Rominger A, et al. Real versus imagined locomotion: a F-FDG PET-fMRI comparison. *2010*. 50:1589-1598.

238. Chou L, Kaufman KR, Walker-Rabatin AE, Brey RH, Basford JR. Dynamic instability during obstacle crossing following traumatic brain injury. *Gait Posture*. 2004;20:245-254.

239. Parikh R, Mathai A, Parikh S, Sekhar G, Thomas R. Understanding and using sensitivity, specificity and predictive values. *Indian J Ophthalmol*. 2008;56(1):45-50.

240. Haines D, Mihailoff G, Bloedel J. The cerebellum. In: *Fundamental Neuroscience*. 2nd editio. New York, NY: Churchill Livingstone; 2002:424-443.

241. Walter H. The Cerebellum. In: *Clinical Methods: The History, Physical, and Laboratory Examinations*. 3rd Editio. Boston: Butterworths; 1990.

242. Singer C, Sanchez-Ramos J, Weiner W. Gait abnormality in essential tremor. *Mov Disord*. 1994;9:193-196.

243. Magolesky J, Singer C. How tandem gait stumbled into the neurological exam: a review. *Neurol Sci*. 2018;39(1):23-29.

244. Fine E, Ionita C, Lohr L. The history of the development of the cerebellar examination. *Semin Neurol*. 2002;22(4):375-384.

245. Bastian A, Thach W. Cerebellar outflow lesions: a comparison of movement deficits resulting in lesions at the levels of the cerebellum and thalamus. *Ann Neurol*. 1995;38:881-892.

246. Lindholm B, Nilsson M, Hansson O. External validation of a 3-step falls prediction model in mild Parkinson's disease. *J Neurol*. 2016;263(12):2462-2469.

247. Aerts M, Esselink R, Abdo W. Ancillary investigations to diagnose parkinsonism: a prospective clinical study. *J Neurol*. 2016;262:346-356.

248. Abdo W, Borm G, Munneke M, Verbeek M, Esselink R, Bloem B. Ten steps to identify atypical parkinsonism. *J Neurol Neurosurg Psychiatry*. 2006;77(1367-69).

249. Cohen H, Mulavara A, Peters B. Sharpening the tandem walking test for screening peripheral neuropathy. *South Med J*. 2013;106:565-569.

250. Guskiewicz KM. Balance assessment in the management of sport-related concussion. *Clin Sport Med*. 2011;30:89-102.

251. NCAA. *Student Athlete Participation: 1981-2016.*; 2016.

252. Buckley T, Oldham J, Caccese J. Postural control deficits identify lingering post-concussion neurological deficits. *J Sport Heal Sci*. 2016;5(1):61-69.

253. Fino P, Becker L, Fino N, Griesemer B, Goforth M, Brolinson P. Effects of recurrent concussion and injury history on instantaneous relative risk of lower extremity injury in Division I collegiate athletes. *Clin J Sport Med*. 2017;[EPub]

254. Lynall R, Mauntel T, Pohlig R, et al. Lower extremity musculoskeletal injury risk after concussion recovery in high school athletes. *J Athl Train*. 2017;52(11): 1028-1034.

255. Guskiewicz KM. Balance Assessment in the Management of Sport-Related Concussion. *Clin Sports Med*. 2011;30(1):89-102.

256. Kerr Z, Dompier T, Snook E, et al. National Collegiate Athletic Association Injury Surveillance System: review of methods for 2004-2005 through 2013-2014 data collection. *J Athl Train*. 2014;49(4):552-560.

257. Buckley TA, Vallabhajosula S, Oldham J, et al. Evidence of a conservative gait strategy in athletes with a history of concussions. *J Sport Heal Sci*. 2015;5(4): 417-423.

258. Caggiano V, Leiras R, Goni-Erro H, et al. Midbrain circuits that set locomotor speed and gait selection. *Nature*. 2018;553(7689):[EPub]

259. McKeon P, Hertel J. Systematic review of postural control and lateral ankle instability, part I: can deficits be detected with instrumented testing. *J Athl Train*. 2008;43(3):293-304.

260. Howell D, Buckley T, Lynall R, Meehan W. Worsening dual-task gait costs after concussion and their association with subsequent sport-related injury. *J Neurotrauma*. 2018;[EPub]

261. Fulton J, Wright K, Kelly M, et al. Injury risk is altered by previous injury: a systematic review of the literature and presentation of causative neuromuscular factors. *Int J Sport Phys Ther*. 2014;9(5):583-595.

262. Kontos A, Deitrick J, Reynolds E. Mental health implications and consequences following sport-related concussion. *Br J Sports Med*. 2016;50:139-140.

263. Moreau M, Langdon J, Buckley T. The lived experience of an in-season concussion amongst NCAA Division I student-athletes. *Int J Exerc Sci*. 2014;7:62-74.

264. Turner S, Langdon J, Shaver G, Graham V, Naugle K, Buckley T. Comparison of psychological response between concussion and musculoskeletal injury in collegiate athletes. *Sport Exerc Perform Psychol*. 2017;6(3):277-288.

265. Martin E, Ressler K, Binder E, Nemeroff C. The neurobiology of anxiety disorders: brain imaging, genetics, and psychoneuroendocrinology. *Psychiatr Clin North Am*. 2009;32(3):549-575.

266. Ford J, Ildefonso K, Jones M, Arvinen-Barrow M. Sport-related anxiety: current insights. *Open access J Sport Med*. 2017;8:205-212.

267. Di Stasi S, Myer G, Hewett T. Neuromuscular training to target deficits associated with second anterior cruciate ligament injury. *J Orthop Sport Phys Ther*. 2013;43(11):777-11.

Appendix A

AIM 1 DEPENDENT VARIABLE DEFINITIONS

Task	Definition	Calculation
ST Gait Initiation (GI)		
APA Duration	The time from APA onset to the second heel strike.	An algorithm uses the 3D acceleration signals from the Opal worn on L5 to quantify the APA and the angular velocities from the left and right foot opals to quantify first step characteristics.
APA First Step Duration	The time-to-peak angular velocity from APA end to heel-strike.	
APA First Step ROM	The integrated angular velocity of the shank from APA end to heel-strike.	
Forward Peak APA Acceleration	Forward trunk peak acceleration from baseline (Peak AP Acc)	
Lateral Peak APA Acceleration	Peak acceleration toward the stance foot from baseline (Peak ML Acc)	
ST Gait		
Gait Speed	Gait speed (m/s)	Gait velocity = distance/time
Cadence	The amount of steps per minute (steps/min)	The Opals calculate cadence from the angular velocity of the pitch axis of the gyroscopes.
Stride Length	The distance between consecutive heel strikes on the same foot (m)	The Opals calculate stride length from the angular velocity of the pitch axis of the gyroscopes.
Double Support Time	The percentage of the gait cycle during which both feet are on the ground (%)	DS= IDS + TDS
Turning		
Turning Duration	The duration of the 180 degree turn	Measured from the lumbar Opal according to mathematical model
Peak Turning Velocity	The peak (95%) angular velocity of the trunk during turning.	
Dual-task (DT)	Participants will perform the same gait protocol as single-task, but will simultaneously complete mini-mental style questions.	
Cognitive Accuracy	(# of correct answers/# of total answers)/*100	
Total Number Correct	Total number of correct answers	

Appendix B

DUAL-TASK DATA COLLECTION SHEET

WALKING TRIAL

				Subtraction											Trial	Trial
trial	**Words**	√ / x	trial	√ / x / o = correct/incorrect/omitted										**Months**	√ / x / o	√ / x / o
___	visit	___	___	85	x6	79	73	67	61	55	49	43	37	December	___	___
___	learn	___	___	64	x7	57	50	43	36	29	22	15	8	November	___	___
___	alert	___	___	95	x6	88	81	74	67	60	53	46	39	October	___	___
___	twist	___	___	71	x6	65	59	53	47	41	35	29	23	September	___	___
___	snack	___	___	98	x7	91	84	77	70	63	56	49	42	August	___	___
___	earth	___	___	66	x7	59	52	45	38	31	24	17	10	July	___	___
___	fence	___	___	61	x6	55	49	43	37	31	25	19	13	June	___	___
___	lemon	___	___	72	x7	65	58	51	44	37	30	23	16	May	___	___
___	crawl	___	___	87	x7	80	73	66	59	52	45	38	31	April	___	___
___	dance	___	___	93	x6	87	81	75	69	63	57	51	45	March	___	___
___	brave	___	___	88	x7	81	74	67	60	53	46	39	32	February	___	___
___	mouse	___	___	70	x7	63	56	49	42	35	28	21	14	January	___	___
___	noble	___	___	69	x6	63	57	51	45	39	33	27	21			
___	guest	___	___	90	x7	83	76	69	62	55	48	41	34			
___	paper	___	___	75	x6	69	63	57	51	45	39	33	27			

___(7) S-T Walk ___(12) D-T Walk

___(8) S-T Walk ___(13) D-T Walk

___(9) S-T Walk ___(14) D-T Walk

___(10) S-T Walk ___(15) D-T Walk

___(11) S-T Walk ___(16) D-T Walk

Appendix C

AIM 1 GAIT INITIATION RAW DATA

Task	Group	Time	n	APA Duration (s)	First Step Duration (s)	First Step ROM (degrees)	Forward Peak APA (g)	Lateral Peak APA (g)
Single Task	Concussion	Baseline	24	0.46 ± 0.17	0.49 ± 0.03	24.58 ± 5.17	0.056 ± 0.028	0.044 ± 0.014
		Acute	18	0.48 ± 0.26	0.49 ± 0.04	26.53 ± 7.74	0.054 ± 0.022	0.043 ± 0.019
		Asymptomatic	23	0.41 ± 0.16	0.48 ± 0.03	27.41 ± 6.37	0.066 ± 0.033	0.048 ± 0.017
		RTP	22	0.47 ± 0.16	0.48 ± 0.03	27.26 ± 9.19	0.052 ± 0.025	0.045 ± 0.016
	Controls	Baseline	28	0.42 ± 0.21	0.48 ± 0.04	23.14 ± 5.32	0.056 ± 0.024	0.043 ± 0.013
		Acute	25	0.43 ± 0.27	0.47 ± 0.06	23.73 ± 6.52	0.057 ± 0.024	0.038 ± 0.012
		Asymptomatic	16	0.40 ± 0.14	0.45 ± 0.04	22.93 ± 5.63	0.064 ± 0.031	0.042 ± 0.012
		RTP	24	0.33 ± 0.12	0.45 ± 0.04	22.23 ± 7.53	0.062 ± 0.033	0.044 ± 0.020
Dual Task	Concussion	Baseline	24	0.44 ± 0.16	0.50 ± 0.07	22.66 ± 5.94	0.045 ± 0.015	0.042 ± 0.019
		Acute	17	0.41 ± 0.14	0.51 ± 0.07	26.76 ± 6.03	0.043 ± 0.017	0.036 ± 0.014
		Asymptomatic	23	0.41 ± 0.15	0.48 ± 0.05	25.31 ± 7.72	0.048 ± 0.029	0.038 ± 0.015
		RTP	22	0.45 ± 0.18	0.48 ± 0.03	24.33 ± 6.58	0.051 ± 0.024	0.043 ± 0.015
	Controls	Baseline	28	0.42 ± 0.14	0.51 ± 0.12	23.57 ± 6.16	0.042 ± 0.017	0.036 ± 0.014
		Acute	25	0.46 ± 0.23	0.48 ± 0.05	24.64 ± 7.19	0.051 ± 0.026	0.035 ± 0.013
		Asymptomatic	19	0.41 ± 0.16	0.47 ± 0.04	23.17 ± 5.86	0.056 ± 0.025	0.037 ± 0.012
		RTP	25	0.39 ± 0.15	0.47 ± 0.05	24.89 ± 13.96	0.054 ± 0.025	0.033 ± 0.013

Appendix D

RAW MEAN ± SD OF THE AIM 1 GAIT VARIABLES

Task	Group	Time	n	Cadence (steps/min)	Double Support (%)	Gait Speed (m/s)	Stride Length (m)
Single Task	Concussion	Baseline	34	111.5 ± 11.2	19.6 ± 4.1	1.18 ± 0.15	1.2 ± 0.1
		Acute	20	113.3 ± 6.1	19.7 ± 1.8	1.13 ± 0.11	1.2 ± 0.1
		Asymptomatic	25	115.1 ± 7.2	18.8 ± 2.3	1.18 ± 0.15	1.2 ± 0.2
		RTP	25	115.5 ± 7.8	18.7 ± 1.9	1.20 ± 0.11	1.2 ± 0.9
	Controls	Baseline	28	113.3 ± 7.7	19.5 ± 2.5	1.13 ± 0.15	1.2 ± 0.1
		Acute	25	116.1 ± 7.5	18.8 ± 2.3	1.17 ± 0.13	1.2 ± 0.9
		Asymptomatic	19	116.4 ± 7.9	18.3 ± 2.3	1.19 ± 0.16	1.2 ± 0.1
		RTP	25	117.5 ± 8.6	18.4 ± 2.8	1.20 ± 0.16	1.2 ± 0.1
Dual Task	Concussion	Baseline	33	102.8 ± 10.9	20.3 ± 3.1	1.06 ± 0.17	1.2 ± 0.1
		Acute	20	105.8 ± 5.4	22.1 ± 2.1	0.96 ± 0.08	1.1 ± 0.1
		Asymptomatic	25	108.4 ± 7.5	21.0 ± 2.3	1.04 ± 0.16	1.1 ± 0.2
		RTP	25	108.6 ± 7.7	21.2 ± 2.3	1.04 ± 0.10	1.1 ± 0.1
	Controls	Baseline	28	106.6 ± 7.7	21.6 ± 2.5	0.98 ± 0.15	1.1 ± 0.1
		Acute	25	110.2 ± 8.2	20.9 ± 2.6	1.04 ± 0.16	1.1 ± 0.1
		Asymptomatic	19	110.1 ± 8.1	20.2 ± 2.5	1.05 ± 0.17	1.1 ± 0.1
		RTP	25	112.3 ± 7.9	20.0 ± 3.0	1.09 ± 0.16	1.1 ± 0.1

Appendix E

RAW MEAN ± SD OF TURNING VARIABLES (AIM 1)

Task	Group	Time	n	Turn Duration (seconds)	Turn Velocity (degrees/second)
Single Task	Concussion	Baseline	34	2.5 ± 0.4	177.4 ± 30.1
		Acute	20	2.3 ± 0.3	180.8 ± 22.1
		Asymptomatic	25	2.2 ± 0.4	213.4 ± 79.0
		RTP	25	2.2 ± 0.3	197.7 ± 25.6
	Controls	Baseline	28	2.3 ± 0.4	185.7 ± 41.1
		Acute	25	2.2 ± 0.3	197.9 ± 37.8
		Asymptomatic	18	2.1 ± 0.3	205.1 ± 46.0
		RTP	25	2.2 ± 0.4	202.4 ± 40.7
Dual Task	Concussion	Baseline	34	2.6 ± 0.4	157.1 ± 26.4
		Acute	20	2.4 ± 0.4	163.2 ± 23.5
		Asymptomatic	25	2.3 ± 0.5	190.3 ± 86.6
		RTP	25	2.4 ± 0.3	181.1 ± 35.7
	Controls	Baseline	28	2.3 ± 0.4	176.9 ± 46.3
		Acute	25	2.3 ± 0.4	188.2 ± 45.1
		Asymptomatic	19	2.3 ± 0.4	190.3 ± 46.6
		RTP	25	2.2 ± 0.3	198.2 ± 45.8

Appendix F

RAW MEAN ± SD OF TANDEM GAIT, BEST TANDEM GAIT, BESS (AIM 2)

	Concussion				Controls			
	n	**Single-Task**	***n***	**Dual-Task**	***n***	**Single-Task**	***n***	**Dual-Task**
Baseline	65	10.14 ± 1.74	38	12.51 ± 3.08	28	10.14 ± 1.97	28	12.11 ± 2.74
Acute	43	10.98 ± 2.35	31	14.42 ± 3.25	25	9.07 ± 1.78	25	11.35 ± 3.03
Asymptomatic	51	9.71 ± 2.03	31	12.09 ± 2.40	21	8.89 ± 1.65	21	10.90 ± 2.60
RTP	46	9.27 ± 1.44	26	11.21 ± 1.85	23	8.64 ± 1.73	23	9.67 ± 2.24

Mean ± SD of BEST tandem gait

	Concussion				Controls			
	n	**Single-Task**	***n***	**Dual-Task**	***n***	**Single-Task**	***n***	**Dual-Task**
Baseline	65	10.97 ± 1.66	38	13.98 ± 3.70	28	10.80 ± 2.00	28	13.32 ± 3.16
Acute	43	11.74 ± 2.51	31	15.70 ± 4.06	25	9.62 ± 1.84	25	12.24 ± 3.15
Asymptomatic	51	10.37 ± 2.23	31	13.47 ± 2.68	21	9.54 ± 1.71	21	11.81 ± 2.77
RTP	46	9.95 ± 1.53	26	12.19 ± 2.06	23	9.06 ± 1.78	23	10.42 ± 2.59

Mean ± SD of MEAN tandem gait

	Concussion		Control	
	n	**BESS Errors**	***n***	**BESS Errors**
Baseline	65	13.6 ± 6.8	28	8.4 ± 3.0
Acute	42	13.5 ± 6.3	25	8.3 ± 2.7
Asymptomatic	52	11.2 ± 6.0	21	6.9 ± 3.7
RTP	46	10.0 ± 5.2	23	7.7 ± 3.0

Appendix G

GROUP AND TIME EFFECTS FOR SINGLE-TASK AND DUAL-TASK BEST AND MEAN TANDEM GAIT (AIM 2)

					95% Confidence Intervals		Mixed Model	
		Group	**Mean**	**Standard Error**	**Lower Bound**	**Upper Bound**	**F**	**p**
Single-Task	**BEST**	Concussion	10.02	0.13	9.76	10.28	13.039	<0.001
		Controls	9.19	0.19	8.81	9.56		
	MEAN	Concussion	10.75	0.14	10.48	11.03	17.128	<0.001
		Controls	9.76	0.20	9.36	10.15		
Dual-Task	**BEST**	Concussion	12.56	0.25	12.07	13.04	7.931	<0.001
		Controls	11.01	0.28	10.46	11.56		
	MEAN	Concussion	13.84	0.30	11.48	16.19	19.320	<0.001
		Controls	11.95	0.34	9.40	14.50		

		Time	Mean	Standard Error	95% Confidence Intervals Lower Bound	95% Confidence Intervals Upper Bound	Mixed Model F	Mixed Model p
Single-Task	BEST	Baseline	10.14	0.21	9.73	10.56	6.154	<0.001
		Acute	10.02	0.24	9.56	10.49		
		Asymptomatic	9.30	0.24	8.83	9.78		
		RTP	8.96	0.24	8.49	9.42		
	MEAN	Baseline	10.88	0.22	10.45	11.32	7.211	<0.001
		Acute	10.68	0.25	10.20	11.16		
		Asymptomatic	9.95	0.25	9.45	10.45		
		RTP	9.51	0.25	9.02	9.99		
Dual-Task	BEST	Baseline	12.31	0.34	11.64	12.98	7.931	<0.001
		Acute	12.88	0.37	12.16	13.60		
		Asymptomatic	11.49	0.39	10.74	12.25		
		RTP	10.44	0.39	9.67	11.21		
	MEAN	Baseline	13.65	0.41	7.90	19.40	7.595	<0.001
		Acute	13.97	0.44	8.11	19.84		
		Asymptomatic	12.64	0.46	6.56	18.72		
		RTP	11.31	0.46	5.55	17.06		

Appendix H

RAW MEAN ± SD OF GAIT INITIATION VARIABLES BETWEEN INJURY GROUPS (AIM 3)

Task	Group	Time	n	APA Duration (s)	First Step Duration (s)	First Step ROM (degrees)	Forward Peak APA (g)	Lateral Peak APA (g)
Single Task	Injured	Baseline	13	0.40 ± 0.09	0.49 ± 0.04	22.88 ± 4.67	0.049 ± 0.021	0.042 ± 0.015
		Acute	10	0.47 ± 0.21	0.49 ± 0.04	25.51 ± 7.86	0.040 ± 0.012	0.040 ± 0.014
		Asymptomatic	12	0.46 ± 0.15	0.48 ± 0.04	26.13 ± 6.43	0.053 ± 0.026	0.041 ± 0.013
		RTP	13	0.46 ± 0.16	0.48 ± 0.03	25.68 ± 7.98	0.049 ± 0.025	0.042 ± 0.017
	Non Injured	Baseline	11	0.47 ± 0.12	0.50 ± 0.03	26.59 ± 5.19	0.040 ± 0.014	0.042 ± 0.023
		Acute	8	0.39 ± 0.16	0.50 ± 0.04	27.80 ± 7.92	0.046 ± 0.023	0.031 ± 0.013
		Asymptomatic	11	0.36 ± 0.16	0.47 ± 0.02	28.80 ± 6.29	0.044 ± 0.032	0.036 ± 0.017
		RTP	9	0.47 ± 0.18	0.47 ± 0.03	29.53 ± 10.79	0.055 ± 0.023	0.042 ± 0.014
Dual Task	Injured	Baseline	13	0.43 ± 0.15	0.50 ± 0.09	22.06 ± 5.31	0.045 ± 0.015	0.042 ± 0.019
		Acute	10	0.39 ± 0.10	0.49 ± 0.05	25.51 ± 7.14	0.043 ± 0.017	0.036 ± 0.014
		Asymptomatic	12	0.41 ± 0.09	0.48 ± 0.04	23.62 ± 9.80	0.048 ± 0.029	0.038 ± 0.015
		RTP	13	0.41 ± 0.17	0.49 ± 0.04	24.78 ± 7.88	0.051 ± 0.024	0.043 ± 0.015
	Non Injured	Baseline	11	0.46 ± 0.19	0.50 ± 0.05	23.37 ± 6.80	0.042 ± 0.017	0.036 ± 0.014
		Acute	7	0.45 ± 0.20	0.54 ± 0.09	28.53 ± 3.78	0.051 ± 0.026	0.035 ± 0.013
		Asymptomatic	11	0.41 ± 0.20	0.48 ± 0.05	27.17 ± 4.26	0.056 ± 0.025	0.037 ± 0.012
		RTP	9	0.51 ± 0.18	0.48 ± 0.02	23.68 ± 4.42	0.054 ± 0.025	0.33 ± 0.013

Appendix I

RAW MEAN ± SD OF GAIT VARIABLES BETWEEN INJURY GROUPS (AIM 3)

Task	Group	Time	n	Cadence (steps/min)	Double Support (%)	Gait Speed (m/s)	Stride Length (m)
Single Task	Injured	Baseline	17	111.6 ± 8.0	20.9 ± 4.8	1.16 ± 0.14	1.22 ± 0.09
		Acute	12	112.4 ± 5.0	20.3 ± 1.7	1.12 ± 0.11	1.17 ± 0.08
		Asymptomatic	14	113.6 ± 7.8	19.1 ± 2.7	1.14 ± 0.14	1.11 ± 0.28
		RTP	15	113.9 ± 6.7	19.4 ± 1.6	1.16 ± 0.10	1.21 ± 0.09
	Non-Injured	Baseline	17	111.3 ± 13.9	18.4 ± 2.8	1.21 ± 0.17	1.24 ± 0.12
		Acute	8	114.7 ± 7.7	19.0 ± 1.8	1.14 ± 0.11	1.18 ± 0.12
		Asymptomatic	11	117.0 ± 6.1	18.5 ± 1.9	1.23 ± 0.16	1.23 ± 0.13
		RTP	10	117.9 ± 9.1	17.7 ± 1.9	1.26 ± 0.10	1.24 ± 0.09
Dual Task	Injured	Baseline	16	105.8 ± 8.0	21.6 ± 3.2	1.04 ± 0.17	1.16 ± 0.15
		Acute	12	104.5 ± 5.9	22.7 ± 2.2	0.93 ± 0.08	1.07 ± 0.07
		Asymptomatic	14	105.9 ± 7.6	21.6 ± 2.0	1.00 ± 0.17	1.02 ± 0.28
		RTP	15	106.4 ± 6.2	22.1 ± 1.9	0.99 ± 0.09	1.12 ± 0.07
	Non-Injured	Baseline	17	105.9 ± 14.3	20.1 ± 3.6	1.09 ± 0.17	1.18 ± 0.10
		Acute	8	107.6 ± 4.3	21.2 ± 1.7	1.00 ± 0.06	1.09 ± 0.10
		Asymptomatic	11	111.4 ± 6.6	20.1 ± 2.4	1.09 ± 0.14	1.16 ± 0.10
		RTP	10	111.8 ± 8.8	19.8 ± 2.1	1.11 ± 0.08	1.16± 0.06

Appendix J

RAW MEAN ± SD OF TANDEM GAIT BETWEEN INJURY GROUPS

		Injured				Non-Injured			
		n	**Single-Task**	***n***	**Dual-Task**	***n***	**Single-Task**	***n***	**Dual-Task**
BEST	**Baseline**	25	10.25 ± 1.75	14	12.87 ± 2.98	40	10.06 ± 1.75	24	12.30 ± 3.18
	Acute	17	10.88 ± 2.61	13	13.76 ± 3.27	26	11.05 ± 2.22	18	14.89 ± 3.25
	Asymptomatic	20	9.63 ± 1.99	15	12.22 ± 2.08	31	9.76 ± 2.09	16	11.97 ± 2.72
	RTP	22	9.24 ± 1.25	13	10.97 ± 1.88	24	9.30 ± 1.62	13	11.45 ± 1.86
MEAN	**Baseline**	25	11.23 ± 1.72	14	14.36 ± 3.66	40	10.80 ± 1.63	24	13.75 ± 3.79
	Acute	17	11.68 ± 2.77	13	15.09 ± 4.33	26	11.78 ± 2.38	18	16.15 ± 3.92
	Asymptomatic	20	10.39 ± 2.22	15	13.60 ± 2.63	31	10.35 ± 2.27	16	13.35 ± 2.81
	RTP	22	9.91 ± 1.38	13	11.75 ± 2.24	24	9.99 ± 1.68	13	12.63 ± 1.85

Appendix K

IRB APPROVAL LETTER

UNIVERSITY OF DELAWARE

RESEARCH OFFICE

210 Hullihen Hall
University of Delaware
Newark, Delaware 19716-1551
Ph: 302/831-2136
Fax: 302/831-2828

DATE:	October 20, 2017
TO:	Thomas Buckley, Ed.D.
FROM:	University of Delaware IRB
STUDY TITLE:	[755528-5] Assessments and Determinants of Concussion Recovery
SUBMISSION TYPE:	Amendment/Modification
ACTION:	APPROVED
APPROVAL DATE:	October 22, 2017
EXPIRATION DATE:	May 19, 2018
REVIEW TYPE:	Expedited Review
REVIEW CATEGORY:	Expedited review per 45 CFR 46.110 (b)(2)

Thank you for your submission of Amendment/Modification materials for this research study. The University of Delaware IRB has APPROVED your submission. This approval is based on an appropriate risk/benefit ratio and a study design wherein the risks have been minimized. All research must be conducted in accordance with this approved submission.

This submission has received Expedited Review based on the applicable federal regulation.

Please remember that informed consent is a process beginning with a description of the study and insurance of participant understanding followed by a signed consent form. Informed consent must continue throughout the study via a dialogue between the researcher and research participant. Federal regulations require each participant receive a copy of the signed consent document.

Please note that any revision to previously approved materials must be approved by this office prior to initiation. Please use the appropriate revision forms for this procedure.

All SERIOUS and UNEXPECTED adverse events must be reported to this office. Please use the appropriate adverse event forms for this procedure. All sponsor reporting requirements should also be followed.

Please report all NON-COMPLIANCE issues or COMPLAINTS regarding this study to this office.

Please note that all research records must be retained for a minimum of three years.

Based on the risks, this project requires Continuing Review by this office on an annual basis. Please use the appropriate renewal forms for this procedure.