

THE CHRONIC EFFECTS OF CONCUSSION ON GAIT

BY

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THESIS

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## ABSTRACT

Concussion has a well-defined, acute effect on motor control with alterations in gait documented up to thirty days post injury. There is a dearth of research examining the chronic effects of concussion on gait. The purpose of this investigation was to examine the effects of concussion in the gait patterns of young adults with and without a history of concussion during single and dual task paradigms. Individuals with (n=28, mean 6.32 years post injury) and without (n=40) a concussion history completed a battery of gait conditions during single and dual-task conditions. Normalized velocity, step length, stride width, number correct from cognitive task, time in single leg stance, and time in double leg stance were the variables of interest. Gait was analyzed using a GAITRite Electronic Walkway system and the Brooks visuospatial cognitive task was used to index cognition. Data analysis was assessed with multiple two-way, repeated measures ANOVAs and correlation analyses. The current investigation found that individuals with a history of concussion spent significantly greater time in double leg stance, significantly decreased time in single leg stance and had slower gait velocity. There was also a significant negative correlation between number of concussions and time in single leg stance and a positive correlation between number of concussions and time in double leg stance double stance percent. These findings suggest that individuals with a history of concussion adopt a more conservative gait strategy, perhaps to reduce the risk of further injury.

*Keywords*     mTBI, Dual task, Cognition, Motor control

*“You have brains in your head. You have feet in your shoes. You can steer yourself in any direction you choose. You're on your own. And you know what you know. You are the one who'll decide where to go.”*

*~ Dr. Seuss*

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# Table of Contents

CHAPTER 1: INTRODUCTION.....	1
<i>Statement of Purpose</i> .....	4
<i>Hypotheses</i> .....	4
CHAPTER 2: LITERATURE REVIEW .....	5
<i>Epidemiology and Metabolic Effect</i> .....	5
<i>Concussion Assessment and Management</i> .....	6
<i>Symptoms</i> .....	7
<i>Neuropsychological Tests</i> .....	8
<i>Balance Tests</i> .....	10
<i>Motor Control</i> .....	12
Short-Term Effects on Gait/Stability and Cognition .....	13
Long-Term Effects on Health and Neurocognitive Function .....	16
<i>Dual Task</i> .....	18
CHAPTER 3: METHODS.....	20
<i>Participants</i> .....	20
<i>Procedure</i> .....	20
<i>Gait Apparatus</i> .....	20
<i>Cognitive Task</i> .....	21
<i>Data Analysis</i> .....	22
CHAPTER 4: MANUSCRIPT .....	23
<i>Abstract</i> .....	23
<i>Introduction</i> .....	24
<i>Methods</i> .....	26
<i>Results</i> .....	29
<i>Discussion</i> .....	30
<i>Conclusions</i> .....	36
APPENDIX A.....	38
APPENDIX B.....	39
APPENDIX C.....	40
APPENDIX D.....	41
REFERENCES .....	42

# Chapter 1

## Introduction

A concussion is defined as a complex pathophysiological process affecting the brain, induced by traumatic biomechanical forces (Aubry, Cantu, Dvorak, Graf-Baumann, Johnston, Kelly, Lovell, McCroy, Meeuwisse, & Schamasch, 2001). Several common features that incorporate clinical, pathological, and biomechanical injury constructs define the nature of a concussive head injury an injury caused by a direct blow to the head, neck, face, or elsewhere on the body with “impulsive” force transmitted to the head, resulting in rapid onset of short lived impairment of function and neuropathological changes, denoting that a concussion reflect a functional disturbance opposed to a structural (Aubry, Cantu, Dvorak, Graf-Baumann, Johnston, Kelly, Lovell, McCroy, Meeuwisse, & Schamasch, 2001). The injury is not one of structural origins, but rather neurometabolic dysfunction of which the changes have been greatly detailed by Giza and Hovda (2001).

Hypermetabolism occurs in the setting of diminished cerebral blood flow and the disparity between glucose supply and demand triggers cellular crisis energy (Giza & Hovda, 2001). This energy crisis makes the brain more susceptible to recurrent concussion due to cells’ inability to cope with the energy demands of the secondary injuries, possibly leading to cell termination (Giza & Hovda, 2001). Metabolic recovery appears to resolve around two weeks postinjury, although Collins et al. (2002) found high school kids may have a longer recovery period. Traditional incidence rates of concussion are thought to approach 250,000 cases annually (Gerberich SG et al. 1983), however, recent changes in the understanding of concussive injuries have resulted in an updated estimate of 1.6-3.8 million concussions resulting from sports participation annually (Langlois, Rutland-Brown, & Wald, 2006).

Individuals who have suffered a concussion usually present delayed verbal and motor responses, confusion, memory deficits, gross incoordination, and inability to focus attention (American Academy of Neurology, 1997). These effects are most commonly presented during the acute stage of concussion. There are two groups of concussion symptoms that can be present, early symptoms (minutes and hours) and late symptoms (days and weeks). The early symptoms include headache, dizziness/vertigo, lack of awareness of surroundings, and nausea and/or vomiting (American Academy of Neurology, 1997). An abbreviated list of late symptoms includes a persistent low-grade headache, light-headedness, poor attention and concentration, anxiety and/or depressed mood, and memory dysfunction (American Academy of Neurology, 1997).

A multitude of investigations have evaluated different techniques to assess concussion. In assessing a concussion, it is important to test the individual's neurological and motor control abilities. A few tests that have been proven to accurately assess an individual's cognitive ability include the Immediate Post-Concussion Assessment and Cognitive Testing (ImPACT), the Standard Assessment of Concussion (SAC), and the Concussion Resolution Index (CRI). Tests which are employed to assess the individual's motor control include the Sensory Organization Test (SOT), and the Balance Error Scoring System (BESS). Recent investigations have analyzed gait and have found significant differences between acutely concussed and matched controls. Although gait analysis is not commonly used in concussion assessment, there are data indicating it has the requisite sensitivity to be used as an evaluative tool. Many investigations have analyzed gait velocity, center of mass (CoM) motion, and center of pressure (CoP) (Chou, Kaufman, Walker-Rabatin, Brey, & Brasford, 2003; Catena, van Donkelaar, & Chou, 2006; Parker, Osternig, van Donkelaar, & Chou, 2007; Catena, van Donkelaar, & Chou, 2009).

It is estimated that 5.3 million Americans (2% of U. S. population) currently have a long-term need in performing daily activities as a result of concussions (<http://www.cdc.gov/ncipc/tbi/TBI.htm>, 2009). While injury location and severity play a major role in the long-term injury consequences, Guskiewicz et al. found that a history of concussions is a risk factor for early onset of Alzheimer's disease (AD) and mild cognitive impairment (MCI) (Guskiewicz, Marshall, Bailes, McCrea, Cantu, Randolph, & Jordan, 2005). Retired athletes with a history of three or more concussions were five-times more likely to be diagnosed with MCI and three times more likely to report memory impairment than players with no history of concussion (Guskiewicz, Marshall, Bailes, McCrea, Cantu, Randolph, & Jordan, 2005). Although Guskiewicz et al. (2005) found no association between recurrent concussion and AD, they did report a higher prevalence in retired athletes compared to the general U. S. male population. Guskiewicz et al. have reported that a lifetime prevalence of depression increases with the number of previous head injury exposure (Guskiewicz, Marshall, Bailes, McCrea, Harding Jr., Matthews, Mihalik, & Cantu, 2007). Omalu et al. also looked at how previous head injuries lead to depression and dementia-related symptoms that eventually lead to the suicide attempts and eventual suicide of a retired NFL player (Omalu, DeKosky, Hamilton, Minster, Kamboh, Shakir, & Wecht, 2006). While the underpinnings of the increased cerebral disease rates were not outlined, others have presented a retired professional football player's autopsy report of medical history, as well as family interviews, to indicate that the subject presented symptoms of Parkinson's syndrome PS and memory deficit due to concussion (Omalu, DeKosky, Minster, Kamboh, Hamilton, & Wecht, 2005). Furthermore, the higher incidence of neurodegeneration reported in former professional athletes parallels motor deficits found in older adults reporting a history of concussion. Indeed, De Beaumont and colleagues were able to show longer cortical

silent period (CSP) times in those with a history of concussion (30 years prior) when the motor cortex was perturbed with transcranial magnetic stimulation (TMS) (De Beaumont L et al. 2009).

Gait studies (i.e. Catena et al., Chou et al., & Parker et al) have extended the evaluation of motor control following concussion and evidenced altered gait patterns in acutely concussed individuals.

*Statement of Purpose:* The purpose of this investigation is to investigate the long-term effects concussion has on gait. Based on the current status of the literature.

*Hypotheses:* We hypothesize that those with a history of concussion will adopt a more conservative gait strategy as indicated by alterations in gait velocity, step length, and stride width. We further hypothesize that those with a history of concussion will perform worse than the controls on the cognitive task during the three cognitive task conditions.

## Chapter 2

### Literature Review

#### *Epidemiology and Metabolic Effect*

A concussion is defined as a complex pathophysiological process affecting the brain, induced by traumatic biomechanical forces (Aubry, Cantu, Dvorak, Graf-Baumann, Johnston, Kelly, Lovell, McCroy, Meeuwisse, & Schamasch, 2001). These forces result in a disruption of the neuronal membranes that can last for 6-24 hours post-injury. This process of axonal stretching causes the opening of the voltage-dependant potassium (K) channels, which leads to a marked increase in extracellular K (Giza & Hovda, 2001). In an effort to restore homeostasis, energy requiring membrane pumps are activated and trigger an increase in glucose consumption (Giza & Hovda, 2001). The sodium-potassium (NA-K) pumps work in an attempt to restore neuronal membrane potential (Giza & Hovda, 2001). In order to keep the NA-K pump functional, glucose metabolism dramatically increases to synthesize the adenosine triphosphate (ATP) required to run the NA-K pump (Giza & Hovda, 2001). Concurrent with the efflux of K, an influx of calcium (Ca<sup>+</sup>) occurs (Giza & Hovda, 2001). In an attempt to control the amount of Ca<sup>+</sup> in the cell, the Ca<sup>+</sup> may be sequestered in the mitochondria, resulting in impaired oxidative metabolism (Giza & Hovda, 2001). Energy demand surpasses energy supply and as a result there is an increase in glycolysis and subsequently lactic acid production is increased (Giza & Hovda, 2001). After the initial period of hyperglycolysis, cerebral glucose consumption diminishes by 24 hours post-injury and remains low for 2-4 weeks post-concussion (Giza & Hovda, 2001). The mechanical stretching and microtubule breakdown, due to increased axonal Ca<sup>+</sup> levels, of the axons may result in membrane disruption and/or depolarization and can last for 6-24 hours post-

injury (Giza & Hovda, 2001). The long-term deficits in memory and cognition that have been noted post-concussion may result from dysfunctional excitatory neurons (Giza & Hovda, 2001).

### *Concussion Assessment and Management*

The diagnosis of an acute concussion involves the assessment of a range of domains including: symptoms – somatic, cognitive, and/or emotional; physical signs; behavioral changes; cognitive impairment; and sleep disturbance (McCrorry, Meeuwisse, Johnston, Dvorak, Aubry, Molloy, & Cantu, 2009). Due to the number of sport related concussions a year it is crucial to follow a systematic on-field or sideline evaluation of a injury. McCrorry et al. (2009) suggest the player should be medically evaluated on site, including an evaluation of player disposition, first aid, concussion assessment, monitoring for deterioration, and preventing them from returning to play on the day of the injury. There are two types of concussion assessment tools that are widely accepted, balance and neuropsychological testing, and a third, neuroimaging, which is only useful in determining further/structural damage to the brain. Balance and neuropsychological tests are covered in detail below. Neuroimaging is primarily used in determining if there is a more serious bleeding in the brain or other structural damage. However, functional Magnetic Resonance Imaging (fMRI) can be used to observe blood flow to specific brain regions related to a cognitive process inherent to task completion and the subsequent metabolic demand (Elleberg, Henry, Macciocchi, Guskiewicz, Broglio, 2009). Following a concussive injury, decreases in blood flow are speculated to represent an impaired functional capacity, and areas of increased blood flow represent increased activity in non-injured areas that are compensating for the injured areas. (Elleberg, Henry, Macciocchi, Guskiewicz, Broglio, 2009).

*Symptoms*

The most efficient way to evaluate for concussion is assessing for the symptoms. Table 1 displays the symptoms from the graded symptoms checklist (GSC), which is used to assess concussion symptoms (McCrea, M, Guskiewicz, K, Marshall, S, Barr, W, Randolph, C, Cantu, R, Onate, J, Yang, J, Kelly, J, 2003).

The three most commonly reported concussion symptoms are headache, dizziness, and confusion (Ellemer, Henry, Macciocchi, Guskiewicz, & Broglio, 2009). In an investigation to test the validity of self-reported symptoms, the GSC symptoms were grouped into three categories of measurement, somatic, neurobehavioral, and cognitive (Piland, Motl, Guskiewicz, McCrea,

Graded Symptom Checklist (GSC)					
Symptom	Time of injury	2-3 Hours postinjury	24 Hours postinjury	48 Hours postinjury	72 Hours postinjury
Blurred vision					
Dizziness					
Drowsiness					
Excess sleep					
Easily distracted					
Fatigue					
Feel "in a fog"					
Feel "slowed down"					
Headache					
Inappropriate emotions					
Irritability					
Loss of consciousness					
Loss or orientation					
Memory problems					
Nausea					
Nervousness					
Personality change					
Poor balance/ coordination					
Poor concentration					
Ringing in ears					
Sadness					
Seeing stars					
Sensitivity to light					
Sensitivity to noise					
Sleep disturbance					
Vacant stare/glassy eyed					
Vomiting					

NOTE: The GSC should be used not only for the initial evaluation but for each subsequent follow-up assessment until all signs and symptoms have cleared at rest and during physical exertion. In lieu of simply checking each symptom present, the ATC can ask the athlete to grade or score the severity of the symptom on a scale of 0-6, where 0=not present, 1=mild, 3=moderate, and 6=most severe.

**Table 1:** Graded Symptoms Checklist (Guskiewicz, Bruce, Cantu, Ferrara, Kelly, McCrea, Putukian, & Valovich McLeod, 2004)

& Ferrara, 2006). Piland et al. (2006) used the 9- and 16-item GSC scale to test the correlation of the groupings. The 9-item scale had a better fit than the 16-item scale, which had its groups constructed as: somatic – headache, nausea, and balance problems; neurobehavioral – sleeping more than normal, drowsiness, and fatigue; and cognitive – feeling “slowed down”, feeling “in a fog”, and difficulty concentrating (Piland, Motl, Guskiewicz, McCrea, & Ferrara, 2006). As seen in investigations by McCrea et al. (2003), individuals that suffered a concussion returned to baseline level within five to seven days post-injury.

### *Neuropsychological Tests*

Neurocognitive testing has been suggested as the most important aspect of the concussion assessment battery. In the modern era, the majority of these tests are administered on computer platforms. The Standard Assessment of Concussion (SAC) is an on-field test of neurostatus that is quick and inexpensive in assessing if an athlete has sustained a concussion (Miller Adamson, Pink, & Sweet, 2007). The largest limitation of the SAC is that the sensitivity declines following the initial 48 hours of the injury (Miller Adamson, Pink, & Sweet, 2007). The components of the SAC consist of an immediate memory portion (focuses on the memorization and regurgitation of five words), an orientation portion (focuses on the month, date, day of the week, year, and time), a concentration portion (focuses on the ability to regurgitate a set of digits, three to five digits, in reverse), and a delayed memory portion (focuses on the ability to repeat the original five words from the immediate memory test) (Miller Adamson, Pink, & Sweet, 2007). Miller et al. reported that there was no significant decrease in SAC scores as the season progressed, so any decline from the baseline performance could be clinically significant, possibly denoting a concussion (Miller Adamson, Pink, & Sweet, 2007). In a NCAA sponsored study, McCrea et al. (2003) measured the acute effects of concussion and the continuous time course to recovery following a concussion using the SAC. Football players (N=1631) were recruited from all three NCAA levels, 94 of which suffered a concussion (McCrea, Guskiewicz, Marshall, Barr, Randolph, Cantu, Onate, Yang, & Kelly, 2003). Contradictory to Miller et al (2007), McCrea's et al. (2003) data suggests that collegiate football players require two days post-injury to fully recover from a sport related concussion.

The ImpACT is a computer based assessment that consists of seven modules that measure multiple aspects of neurocognitive function including: verbal memory composite, visual

memory composite, visual motor speed composite, and reaction time composite (Lovell, Collins, Iverson, Johnston, Bradley, 2004). This cohort found that memory was significantly, negatively affected three days post-injury, however returned to baseline level by six days (Lovell, Collins, Iverson, Johnston, Bradley, 2004). There was no change between baseline reaction time or processing speed scores at three days post-injury, however there was a significant difference between three and six days indicating better than baseline performance (Lovell, Collins, Iverson, Johnston, Bradley, 2004). Collins et al. used baseline and post-injury neuropsychological testing to assist team medics in making a return to play decision by using the ImPACT to evaluate the relationship between concussion history and the on-field presentation of symptoms subsequent to a concussion (Collins, Lovell, Iverson, Cantu, Maroon, & Field, 2002). The study group consisted of 173 high school athletes, of which all had known concussion histories (Collins, Lovell, Iverson, Cantu, Maroon, & Field, 2002). Collins et al. reported that athletes with a history of concussions were more susceptible to experiencing an on-field loss of consciousness (LOC) as well as subsequent concussion (Collins, Lovell, Iverson, Cantu, Maroon, & Field, 2002). Based on ImPACT data, Collins et al. specifically noted that athletes with a self reported history of three or more concussions were nine times more likely to exhibit three or four abnormal markers of injury (Collins, Lovell, Iverson, Cantu, Maroon, & Field, 2002).

Another assessment tool that is used is the CRI, which is an internet based neuropsychological test, consisting of six sub-tests that evaluate cognitive function, which runs less than 25 min for baseline and 20 min for post-injury assessment (Erlanger, Saliba, Barth, Almquist, Webright, & Freeman, 2001). The sub-tests focus on memory, learning, and informational processing speed (Erlanger, Saliba, Barth, Almquist, Webright, & Freeman, 2001). The scores from these measures are compiled from three speed scores, simple reaction time,

complex reaction time, and processing speed index, as well as two error scores, simple reaction time errors and complex reaction time errors (Broglio, Ferrara, Piland, & Anderson, 2006).

Erlanger et al. tested 384 athletes (both collegiate and high school) to see how reliable the CRI is at assessing postconcussive symptoms (Erlanger, Saliba, Barth, Almquist, Webright, & Freeman, 2001). 26 athletes sustained a concussion, of which 14 underwent follow-up testing using the CRI until all self-reported symptoms were resolved, at one to two day intervals up to two weeks post-injury (Erlanger, Saliba, Barth, Almquist, Webright, & Freeman, 2001). The preliminary results indicate that the CRI could be used as a method for assessing and tracking resolution of postinjury symptoms (Erlanger, Saliba, Barth, Almquist, Webright, & Freeman, 2001).

### *Balance Tests*

The Sensory Organization Test (SOT) is a testing protocol that assesses the stability of sensory function and balance performance (Dickin & Clark, 2007). The test manipulates visual and somatosensory inputs through all six testing conditions, allowing for the subjects' postural control to be assessed (Dickin & Clark, 2007). The six conditions for the SOT test use the following environments: eyes open with stable support surface and stable visual surround; eyes closed with stable support surface; eyes opened with a stable support surface and a sway-referenced surround; eyes open with a sway-referenced support and stable visual surround; eyes closed with a sway-referenced support; and eyes open with both support surface and visual surround sway-referenced (Dickin & Clark, 2007). Dickin & Clark (2007) reported that the equilibrium score for each of the six conditions of the SOT are reliable after two SOT tests have been administered. In another study that used the SOT test, 22 collegiate athletes were recruited (11 who suffered a concussion and 11 controls) to measure their postural stability (Guskiewicz, Riemann, Perrin, & Nashner, 1997). Guskiewicz et al. (1997) claimed that the SOT was used

because of its ability to easily isolate sensory inputs providing information about the postural system. The data indicated that the overall postural stability decreased until about three days post-injury, suggesting that an athlete who has suffered a concussion be held out of play at least three days post-injury (Guskiewicz, Riemann, Perrin, & Nashner, 1997; Guskiewicz, Ross, Marshall, 2001). Sosnoff et al. (in press) investigated a concussed subject's ability to maintain static balance while completing the SOT and report that subjects with a history of concussion increased their anterior-posterior postural sway when the postural task became more difficult (Sosnoff, Broglio, Shin, & Ferrara, in press). A more recent investigation, using a longer testing period, found that individuals that suffered a concussion had significantly different balance ten days post-injury (Peterson, Ferrara, Mrazik, Piland, Elliot, 2003). This indicates that the SOT may be sensitive enough to assess a concussion for longer than the noted three to five days.

The Balance Error Scoring System (BESS) is a test of postural stability where three different stances – double leg stance, single leg stance, and tandem leg stance (one foot directly behind the other) - are used for three different difficulty levels (Guskiewicz, Ross, & Marshall, 2001). The different stances would be performed on a sturdy surface, as well as unstable surface, such as a foam mat and would not begin until the subjects' eyes were closed, with 20-second trials (Guskiewicz, Ross, & Marshall, 2001). The performances of these tests are graded on how many errors the subject commits during the 20-second trial (Guskiewicz, Ross, & Marshall, 2001). Anytime an athlete skewed from the initial 30 degree angle of the hip, opened their eyes, put their second foot down, or strayed from the test position the subject received a one point deduction from their final score (Guskiewicz, Ross, & Marshall, 2001). The investigation presents significant findings post-injury day 1 (significantly different from baseline) and significant group differences between groups during the three testing days post-injury

(Guskiewicz, Ross, & Marshall, 2001). The injured group returned to baseline level by post-injury day 3 (Guskiewicz, Ross, & Marshall, 2001). Based on the findings of this study, the BESS passes as a practical, valid, and cost effective method of objectively assessing postural stability in an athlete that might be suffering a concussion (Guskiewicz, Ross, & Marshall, 2001).

### *Motor Control*

Static balance is not possible without the afferent signaling from the peripheral nervous system (PNS) to the central nervous system (CNS). It is the acquisition and conversion of stimuli from the muscles, tendons, joints, and deep tissues by the PNS that allows the motor components (cerebellum and basal ganglia) and motor control centers (spinal, brain stem, and cerebral cortex) to react appropriately to an event (Lephart & Fu, 2000). Somatosensory inputs, primarily tactile and proprioceptive, are integrated with vestibular and visual signals in the brain stem to assist in the control of autonomic tasks such as postural equilibrium (Lephart & Fu, 2000). Proprioceptive signals originate from sensory receptors in joint, muscle, and cutaneous tissue (Lephart & Fu, 2000). An accepted definition of neuromuscular control is an unconscious efferent response to afferent signals concerning dynamic joint stability, for the concern of this paper the focus of stability will encompass balance – the ability to maintain the center of gravity (COG) under the body's base of support- and gait (Lephart & Fu, 2000).

Previous experience of events and outcomes can be used as a feedforward mechanism that will prepare the motor control system for comparison with the feedback information that comes from a specific event (Schmidt & Lee, 2005). This feedforward mechanism can be used in the detection of errors and the corrections of the error, promoting maintenance of balance and gait stability (Schmidt & Lee, 2005). According to Schmidt and Lee (2005) there are two types

of feedback information, inherent and augmented. Inherent feedback occurs without supplemental information from an outside source, whereas augmented feedback comes from an outside source that is supplemental to the inherent feedback (Schmidt & Lee, 2005). Maintaining postural stability requires the tandem use of the feedforward and feedback mechanisms.

As previously discussed the SOT and BESS are used to analyze an individual's balance when suspected of receiving a concussion. Guskiewicz (2001) found that there is a decrease in postural stability, possibly resulting from damage to the peripheral receptors or damage to the brain stem. The SOT system tests the vestibular system in the eyes closed conditions, specifically condition five (eyes closed and moving floor), thus any damage to the vestibular receptors or to the brain stem would appear to affect the outcomes for the two conditions. Similarly the BESS is completed with eyes closed, so any disruption of the vestibular receptors or brain stem activity would logically impair a concussed individual's ability to maintain balance or gait stability.

Having looked at the symptoms, neuropsychological and balance testing investigations, there is evidence that most acute effects resolve within five to seven days post-injury; however there is still the two week window in which metabolic changes have been noted.

#### *Short-term effects on gait/stability and cognition*

Changes in motor control have been noted following concussion for some time. Within the last 15 years postural control deficits have been reported. More recently, a plethora of research has investigated how gait may be affected in the post-injury state (Catena, van Donkelaar, & Chou, 2006, 2006; Parker, Osternig, van Donkelaar, & Chou, 2007). Concussed individuals show more center of mass (COM) motion in the coronal plane, than their control counterparts (Catena, van Donkelaar, & Chou, 2006). The subjects who had sustained a concussion were tested within the 48-hour window post-injury (Catena, van Donkelaar, & Chou,

2006). The subjects were asked to walk in a single task and two dual task situations (Catena, van Donkelaar, & Chou, 2006). In an investigation completed by the same collaborators, an obstacle condition was used instead of a second dual task because the data proved to be insignificant for that particular condition (Catena, van Donkelaar, & Chou, 2006). Parker et al. (2007) completed a similar investigation where they tested concussed subjects within 48-hours post-injury at different intervals: 2, 5, 14, and 28 days; however, only a single task and dual task situation were employed for testing (Parker, Osternig, van Donkelaar, & Chou, 2007). In each of these studies, it was reported that individuals with a concussion showed more balance instability in the dual task situations than the single task and also adopted a more conservative gait strategy than their matched, control counterparts (Catena, van Donkelaar, & Chou, 2006, 2006; Parker, Osternig, van Donkelaar, & Chou, 2007). Chou et al. (2004) similarly found that the concussed individuals had a slower gait velocity and shorter stride length. Parker and colleagues noted that the concussed subjects showed a slower gait on day two than they did on the final testing day (day 28) (Parker, Osternig, van Donkelaar, & Chou, 2007). The two Catena studies indicate that an increased medial-lateral sway in concussed individuals – even though they were adopting a more conservative gait strategy with slower velocities – support the idea that the concussed individuals have a dysfunction in balance (Catena, van Donkelaar, & Chou, 2006, 2006). Parker and colleagues went a step further to suggest that balance dysfunction can last up to a month post injury (Parker, Osternig, van Donkelaar, & Chou, 2007). A study completed by Chou and colleagues looked at how concussed subjects would be able to react to obstacles in their path (Chou, Kaufman, Walker-Rabatin, Drey, & Brasford, 2004). The subjects were instructed to perform a level walk (no obstacles), proceeded by walking over obstacles set at 2.5%, 5%, 10%, and 15% of their individual heights (Chou, Kaufman, Walker-Rabatin, Drey, & Brasford, 2004).

Perhaps the most interesting data to come out of the study is that the concussed subjects displayed faster peak medial-lateral COM velocities during the weight-shifting period of the gait (Chou, Kaufman, Walker-Rabatin, Drey, & Brasford, 2004). This is concurrent with the data that Catena et al. (2006) produced in a later study noted above. It is inferred that the increased medial-lateral COM velocities displayed by the concussed subjects could lead to their feeling of instability (Chou, Kaufman, Walker-Rabatin, Drey, & Brasford, 2004).

A recent case study used an obstacle trial, an unobstructed trial, and a trial with visual task to better understand the effects of concussion on gait (Fait, McFadyen, Swaine, & Cantin, 2009). Nine days postinjury, the 18 year old junior hockey player was cleared to return to play since he was showing no medical symptoms (Fait, McFadyen, Swaine, & Cantin, 2009). Subject's baseline values were present from an earlier study so data was collected seven and 30 days postinjury (Fait, McFadyen, Swaine, & Cantin, 2009). One difference between this study and the previously mentioned studies is that the subject was asked to circumvent around an obstacle in the path as opposed to step over (Fait, McFadyen, Swaine, & Cantin, 2009). The subjects reported return to baseline neurocognitive function by day 14, however, still presented problems with multitask situations up to 30 days post-concussion (Fait, McFadyen, Swaine, & Cantin, 2009).

Further research has looked deeper into the idea that there is a neurodegenerative effect in subjects who have suffered a concussion. Gosselin et al. suggest that even in the absence of symptoms, concussions may cause abnormal neurophysiological patterns when responding to attention demanding tasks (Gosselin, Theriault, Leclerc, Montplaisir, & Lassonde, 2006). Event related potentials (ERPs) were measured in concussed individuals when presented with dichotic sequences of standard and deviant tones (Gosselin, Theriault, Leclerc, Montplaisir, & Lassonde,

2006). When compared with nonconcussed athletes, the concussed showed a reduction in the amplitude of early and late ERPs, even if they did not present symptoms (Gosselin, Theriault, Leclerc, Montplaisir, & Lassonde, 2006).

#### *Long-term effects on health and neurocognitive function*

There are a plethora of studies reporting on the short-term effects of concussion on balance and gait, yet there is a dearth of knowledge that analyzes the effects on gait and stability long-term. Instead, the focus turns to the neurological effects and the health deficits associated with brain damage (Guskiewicz, Marshall, Bailes, McCrea, Harding Jr., Matthews, Mihalik, & Cantu, 2007; Guskiewicz, Marshall, Bailes, McCrea, Cantu, Randolph, & Jordan, 2005; Broglio, Pontifex, O'Connor, & Hillman, (2009); Gaetz, Goodman, & Weinberg, 2000; Gosselin, Theriault, Leclerc, Montplaisir, & Lassonde, 2006; Omalu, DeKosky, Minster, Kamboh, Hamilton, & Wecht, 2005; and Omalu, DeKosky, Minster, Kamboh, Shakir, & Wecht, 2006). The increased risk of depression, memory impairment, MCI, and AD have been identified as possible long term consequences of concussions, specifically recurrent concussions (Guskiewicz, Marshall, Bailes, McCrea, Harding Jr., Matthews, Mihalik, & Cantu, 2007; Guskiewicz, Marshall, Bailes, McCrea, Cantu, Randolph, & Jordan, 2005). Recent work has reported that concussions can be a risk factor for chronic depression, as seen in retired NFL athletes who also happen to be World War II veterans (Guskiewicz, Marshall, Bailes, McCrea, Harding Jr., Matthews, Mihalik, & Cantu, 2007). A total of 3683 subjects received a general health questionnaire that consisted of the Short Form 36 Measurement Model for Functional Assessment of Health and Well-Being (SF-36) (Guskiewicz, Marshall, Bailes, McCrea, Harding Jr., Matthews, Mihalik, & Cantu, 2007). 2552 returned the questionnaire, of which 595 reported three or more concussions; these individuals were three times more likely to be diagnosed with

depression, whereas those with one or two concussions were only one and a half times more likely to be diagnosed with depression (Guskiewicz, Marshall, Bailes, McCrea, Harding Jr., Matthews, Mihalik, & Cantu, 2007). A precursor to this study was completed by Guskiewicz et al. in which they collected the original questionnaires and then replied to 1754 and an informant (spouse or close relative), of the 3683, who were 50 years or older, with a second survey (Guskiewicz, Marshall, Bailes, McCrea, Cantu, Randolph, & Jordan, 2005). The second questionnaire was used to assess MCI according to the American Academy of Neurology (Guskiewicz, Marshall, Bailes, McCrea, Cantu, Randolph, & Jordan, 2005). Based on the data returned by the subjects and the informant, analysis shows that recurrent concussions may be a risk factor for late-life memory impairment, MCI, and Alzheimer's (Guskiewicz, Marshall, Bailes, McCrea, Cantu, Randolph, & Jordan, 2005).

Guskiewicz and colleagues did not investigate the structural underpinnings supporting these changes. Omalu et al. however, conducted a case study in which an autopsy was completed on a retired NFL athlete who had a medical history of a deficit in memory and judgment and showed parkinsonian symptoms (Omalu, DeKosky, Minster, Kamboh, Hamilton, & Wecht, 2005). The autopsy was completed to see if there is a link between professional football and chronic traumatic encephalopathy (CTE) based on neurodegenerative changes (Omalu, DeKosky, Minster, Kamboh, Hamilton, & Wecht, 2005). Characteristics of CTE include sparse to many neurofibrillary tangles (NFTs) in the neocortex, neocortical theta-immunopositive neuritis in the neuropil, and neocortical diffuse amyloid plaques with or without neuritic plaques (Omalu, DeKosky, Minster, Kamboh, Hamilton, & Wecht, 2005). The conclusion of the autopsy did not link professional football to CTE, but indicated further need of research (Omalu, DeKosky, Minster, Kamboh, Hamilton, & Wecht, 2005). A second autopsy of

a retired NFL athlete confirms a case of CTE (Omalu, DeKosky, Minster, Kamboh, Hamilton, & Wecht, 2006). Noted as a possible risk of concussions (Guskiewicz, Marshall, Bailes, McCrea, Harding Jr., Matthews, Mihalik, & Cantu, 2007), this subject suffered from a progressive major depressive disorder following retirement (Omalu, DeKosky, Minster, Kamboh, Hamilton, & Wecht, 2006). This second autopsy confirmed the presence of abnormal metabolism and wide-spread neuronal and neuropil accumulation of cytoskeletal proteins, which has been suggested as components of delayed neurological symptoms of a single or repeated concussion(s) (Omalu, DeKosky, Minster, Kamboh, Hamilton, & Wecht, 2006).

Broglio et al. also found that deficits in the neurological system were still present after symptoms had disappeared, and were present up to three years post injury (Broglio, Pontifex, O'Connor, & Hillman, 2009). Even when a subject presents no symptoms and has normal cognitive ability, neurological deficits still appear in the assessment of ERPs. A specific ERP, P3, was analyzed to determine if multiple concussions will produce a cumulative reduction in the functional capacity (Gaetz, Goodman, & Weinberg, 2000). Gaetz et al. (2000) found that subjects who had suffered three or more concussions have significantly longer P3 latencies compared to subjects who have not suffered a concussion. Gaetz et al. (2000) also noted that P3 latency was also significantly correlated to higher self-report of memory problems, indicating a relationship to cognitive issues.

### *Dual Task*

Current concussion research has separately focused on cognitive and motor testing as a means to assess recovery following concussion (Parker, Osternig, van Donkelaar, & Chou, 2007). Dual task conditions are used to prevent the subject from focusing all of their cognitive ability on maintaining stability during their gait – thus more clinically applicable. A couple of

commonly used cognitive tasks are the spelling of a common five-letter word, continuous subtraction by a certain digit, and reciting the months of the year in reverse order (Catena, van Donkelaar, & Chou, 2007). It is widely accepted that there is a certain amount of effort needed for each task and the investment of less than the allotted effort will cause a deterioration of the performance (Kahneman, 1973). This is one of the assumptions noted by Siu & Woollacott (2005). Siu & Woollacott (2005) observed the ability of subjects' ability to flexibly allocate attention between postural and cognitive tasks. Each participant completed four different conditions; visual spatial memory tasked with the postural task, performance of the two tasks with instructions to focus on the postural task; performance of the two tasks with instructions to focus on the visual memory spatial memory task, and baseline (Siu & Woollacott, 2005). Siu & Woollacott (2005) found that postural stability has a higher priority under dual task contexts. "Tie-breaking" rules are consistently applied in cases of simultaneous stimuli (Kahneman, 1973). Concussed individuals are less able to constrain their output task demands, which is similar to the concept that investment of less than the allocated effort per task will ultimately result in the deterioration of the task (Sosnoff, Broglio, Shin, & Ferrara, in press; Kahneman, 1973).

## **Chapter 3**

### **METHODS**

#### *Participants*

A total of 68 young adults (37 males/31 females,  $20.8 \pm 1.9$  yrs,  $171.0 \pm 9.8$  cm,  $74.5 \pm 14.8$  kg) completed the investigation. Participants were divided into two groups based on self-reported history of concussion: 28 were placed in the concussion group and 40 in the non-concussed group. As implemented elsewhere (Guskiewicz et al., 2007; Guskiewicz et al., 2005) concussion reports were based on diagnoses made by a medical professional (eg physician). The protocol and experimental procedures were approved by the Institutional Review Board with written informed consent provided by each participant prior to testing.

#### *Procedure*

The experiment consisted of a single 30-min testing session in which the participants completed a demographic and health history questionnaire to obtain detailed information about the number of previous concussions, the approximate date, and a brief description of each injury. Each participant was also screened for lower limb and back injuries, illness, and current information about medication that could alter balance and gait. Participants then completed five trials of each of the four single and dual-task conditions (described below) while walking across a GAITRite electronic walkway (CIR Systems, Inc. Havertown, PA). Administration of the four walking conditions and the single, seated/static cognitive task were completed in a randomized fashion.

#### *Gait Apparatus*

Gait was assessed using a 3.7m long GAITRite electronic walkway connected to a computer with the corresponding GAITRite software. A total of 13,824 sensors covering the walkway recorded the temporal and spatial parameters of gait. There were a total of four gait conditions, all of which were completed at a self-selected pace. The four conditions included: Walk – a flat walk with no cognitive task or obstacles; Walk-Cognitive – flat walk while completing a cognitive task, but no obstacles; Obstacle – walk with the obstacles present, but no cognitive task; Obstacle-Cognitive – walk while completing a cognitive task and obstacles present. Two foam blocks (29.5 cm high) were used as obstacles placed on the walkway, splitting it into thirds.

### *Cognitive Task*

Brooks' Spatial Memory Task was implemented as the cognitive task during the dual-task conditions. The task was chosen for its ability to tax the visuospatial component of cognitive processing, which has been linked to an increase in the cognitive-motor association in acute injuries (Sosnoff, Broglio, & Ferrara, 2008). Brooks' Task has been described elsewhere in detail (Brooks, 1967). Briefly, completion of the task required the participant to listen to an audio track describing the placement of digits 1 through 8 placed in an imaginary 4x4 grid. The digits were always in numerical order from 1 to 8 and placed in straight directionally connected squares with no square being used more than once per audio track. Once the audio track was complete, the participant described the position of each digit while completing walking Conditions 2, 4, or while seated in a chair [Condition 5 (Cognitive)]. There were a total of 24 pre-recorded tracks, each lasting approximately 20 seconds, that were randomly played during the five trials of testing for each condition. The participants were given no instruction to focus on either the gait or cognitive task.

### *Data Analysis*

Based on the current status of the literature regarding the persistent effects of concussion on gait, we conducted a two tier data analysis. A primary analysis was conducted on the following variables for their known relationship with acute concussive injuries: normalized velocity (ie velocity divided by average leg length), step length, stride width, and the number correct from the cognitive task. A secondary, exploratory analysis was performed on double support percent (ie % time of the gait cycle in double leg stance), and single support percent (ie % time of the gait cycle in single leg stance). A detailed description of each of these variable can be found elsewhere(2006). The average performance for each testing condition for each variable was used to provide descriptive information (mean±SD) and complete multiple two-way (condition X group) Analyses of Variance (ANOVAs) with repeated measures on the condition to analyze the gait and cognitive data. Mauchly's test evaluated for sphericity violations with a Greenhouse-Geisser correction as indicated. In the event of significant main effects, post-hoc analyses were completed using a Bonferroni correction for multiple analyses. Lastly, to evaluate a possible relationship between previous injuries and gait performance, Spearman's Rho correlational analyses were conducted between the total number of injuries and the variables of interest. All analyses were conducted using SPSS Version 17.0 (SPSS Inc., Chicago, IL) with significance set *a priori* at  $p < 0.05$ .

## Chapter 4 Manuscript

### *ABSTRACT*

Concussion has a well-defined, acute effect on motor control with alterations in gait documented up to thirty days post injury. There is a dearth of research examining the chronic effects of concussion on gait. The purpose of this investigation was to examine the effects of concussion in the gait patterns of young adults with and without a history of concussion during single and dual task paradigms. Individuals with (n=28, mean 6.32 years post injury) and without (n=40) a concussion history completed a battery of gait conditions during single and dual-task conditions. Normalized velocity, step length, stride width, number correct from cognitive task, time in single leg stance, and time in double leg stance were the variables of interest. Gait was analyzed using a GAITRite Electronic Walkway system and the Brooks visuospatial cognitive task was used to index cognition. Data analysis was assessed with multiple two-way, repeated measures ANOVAs and correlation analyses. The current investigation found that individuals with a history of concussion spent significantly greater time in double leg stance, significantly decreased time in single leg stance and had slower gait velocity. There was also a significant negative correlation between number of concussions and time in single leg stance and a positive correlation between number of concussions and time in double leg stance double stance percent. These findings suggest that individuals with a history of concussion adopt a more conservative gait strategy, perhaps to reduce the risk of further injury.

*Keywords* mTBI, Dual task, Cognition, Motor control

## *INTRODUCTION*

Concussion as been described as a diffuse brain injury (McCrory et al., 2009) affecting multiple brain functions including neurocognitive processes and motor control (Broglia & Puetz, 2008). Traditional incidence rates of concussion are thought to approach 250,000 cases annually (Gerberich et al., 1983), however more recent data has suggested that sport related concussions may eclipse previous reports with an estimated 1.6 to 3.8 million injuries per year (Langlois et al., 2006). The effects concussion has on long term cognitive and motor health are currently being elucidated, but it is estimated that 5.3 million Americans, approximately 2% of the United States population, have disabilities associated with brain trauma (National Center for Injury Prevention and Control, 2001). The influence this has on medical care necessitates greater clarity of concussion's persistent effects.

Until recently, there has been a plethora of work clarifying the acute effects of concussion on cognitive and motor functioning (Broglia & Puetz, 2008). Much of this work has focused on impaired balance and gait in the days and weeks following injury. Following subjective reports of headache, dizziness and instability are the second most commonly reported symptoms (65% of concussed athletes) (Elleberg et al., 2009). Standard clinical evaluations for balance deficits (eg Romberg's test) are insensitive to balance decrements following concussion, necessitating the use of more effective evaluation techniques, like the Sensory Organization Test (SOT) and Balance Error Scoring System (BESS). Evaluations of concussed young adults on the SOT and BESS indicate impaired postural stability up to three to five days post-injury (Guskiewicz et al., 2001; Guskiewicz et al., 1997). Others have reported balance decrements as long as ten days post-concussion in a similar cohort evaluated with the SOT

(Peterson et al., 2003). While the use of postural control evaluations have provided new insight into concussion's acute effects, they are criticized for only evaluating static balance.

Gait studies have extended the evaluation of motor control following concussion and evidenced altered gait patterns in acutely concussed individuals. Initial investigations revealed slower walking speeds and shorter stride length when concussed individuals were evaluated shortly after injury (Chou et al., 2004). Additional work showed that concussed young adults, evaluated within 48 hours of injury, have greater center of mass (COM) motion in the coronal plane (Catena et al., 2007). Parker and colleagues reported that concussed individuals had significantly slower velocity while walking and performing a cognitive task (ie dual task) throughout a four week post-injury testing period (Parker et al., 2006). These individuals also had increased center of mass (COM) sway and sway velocity than the controls during the testing period. Collectively these results suggest that in the acute stage of injury, concussed young adults adopt a more conservative gait strategy to maintain stability and decrease their risk of further injury from falling.

While the results of neurocognitive and motor control deficits in the acute stage of injury have been well defined, there is an overall dearth of knowledge addressing the persistent effects of concussion. The initial work evaluating this phenomena in retired professional football players suggests that multiple concussions may be a risk factor for the early expression of late-life memory impairment, mild cognitive impairment (MCI), and Alzheimer's disease (AD) (Guskiewicz et al., 2005). A more recent study involving a similar cohort reported that a lifetime prevalence of depression and feelings commonly referred to as depression are three times more likely in former professional athletes reporting three or more concussions across their careers (Guskiewicz et al., 2007). Likewise, the higher incidence of neurodegeneration reported in

former professional athletes parallels motor deficits found in older adults reporting a history of concussion. De Beaumont and colleagues were able to show longer cortical silent period (CSP) times in those with a history of concussion (30 years prior) when the motor cortex was perturbed with transcranial magnetic stimulation (TMS) (De Beaumont, Theoret, Mongeon, Messier, Leclerc, Tremblay, Ellemberg, & Lassonde, 2009). This finding suggests that motor deficits in both balance and gait identified in the acute stage of injury may persist into later life.

Therefore, the main objective of this study was to evaluate the gait patterns of young adults with and without a concussion history. Based on the current status of the literature, we hypothesize that those with a history of concussion will adopt a more conservative gait strategy as indicated by alterations in gait velocity, step length, and stride width. We further hypothesize that those with a history of concussion will perform worse than the controls on the cognitive task during the three cognitive task conditions.

## *METHODS*

### *Participants*

A total of 68 young adults (37 males/31 females,  $20.8 \pm 1.9$  yrs,  $171.0 \pm 9.8$  cm,  $74.5 \pm 14.8$  kg) completed the investigation. Participants were divided into two groups based on self-reported history of concussion: 28 were placed in the concussion group and 40 in the non-concussed group. As implemented elsewhere (Guskiewicz et al., 2007; Guskiewicz et al., 2005) concussion reports were based on diagnoses made by a medical professional (eg physician). The protocol and experimental procedures were approved by the Institutional Review Board with written informed consent provided by each participant prior to testing.

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processing, which has been linked to an increase in the cognitive-motor association in acute injuries(Sosnoff et al., 2008). Brook’s Task has been described elsewhere in detail (Brooks, 1967). Briefly, completion of the task required the participant to listen to an audio track describing the placement of digits 1 through 8 placed in an imaginary 4x4 grid. The digits were always in numerical order from 1 to 8 and placed in straight directionally connected squares with no square being used more than once per audio track. Once the audio track was complete, the participant described the position of each digit while completing walking Conditions 2, 4, or while seated in a chair [Condition 5 (Cognitive)]. There were a total of 24 pre-recorded tracks, each lasting approximately 20 seconds, that were randomly played during the five trials of testing for each condition. The participants were given no instruction to focus on either the gait or cognitive task.

#### *Data Analysis*

Based on the current status of the literature regarding the persistent effects of concussion on gait, we conducted a two tier data analysis. A primary analysis was conducted on the following variables for their known relationship with acute concussive injuries: normalized velocity (ie velocity divided by average leg length), step length, stride width, and the number correct from the cognitive task. A secondary, exploratory analysis was performed on double support percent (ie % time of the gait cycle in double leg stance), and single support percent (ie % time of the gait cycle in single leg stance). A detailed description of each of these variable can be found elsewhere(2006). The average performance for each testing condition for each variable was used to provide descriptive information (mean±SD) and complete multiple two-way (condition X group) Analyses of Variance (ANOVAs) with repeated measures on the condition to analyze the gait and cognitive data. Mauchly’s test evaluated for sphericity violations with a

Greenhouse-Geisser correction as indicated. In the event of significant main effects, post-hoc analyses were completed using a Bonferroni correction for multiple analyses. Lastly, to evaluate a possible relationship between previous injuries and gait performance, Spearman's Rho correlational analyses were conducted between the total number of injuries and the variables of interest. All analyses were conducted using SPSS Version 17.0 (SPSS Inc., Chicago, IL) with significance set *a priori* at  $p < 0.05$ .

## RESULTS

Descriptive information on the 68 participants enrolled in the investigation can be found in Appendix A. Analysis of the primary variables of interest produced no significant difference between groups or conditions ( $p$ 's  $> 0.05$ ), with the exception of normalized velocity. There was a violation to sphericity ( $W_5 = .46$ ,  $p < 0.00$ ) so the Greenhouse-Geisser correction was implemented, revealing a significant group by condition interaction ( $F_{2.05, 134.96} = 3.49$ ,  $p = 0.03$ ). Further analyses indicated a condition main effect ( $F_{2.05, 134.96} = 105.2$ ,  $p < 0.00$ ) whereby the normalized velocity in each condition was significantly different than all other conditions ( $p$ 's  $< 0.05$ , see Appendix D). Furthermore, the concussed participants demonstrated a significantly slower gait velocity than the control group while completing Walk condition ( $1.46 \pm .14$  vs  $1.56 \pm .19$  m/s;  $F_{1,66} = 5.43$ ,  $p = .02$ ).

The exploratory analysis indicated significant condition ( $W_5 = .73$ ,  $p < .00$ ,  $F_{2.44, 160.75} = 194.93$ ,  $p < .00$ ) and group ( $F_{1,66} = 11.66$ ,  $p < .01$ ) main effects for double support percent. Post-hoc analyses indicated the double stance percent for each condition was significantly different from all other conditions ( $p$ 's  $< 0.05$ ). Further, the concussed and non-concussed groups differed significantly on the Walk ( $F_{1,66} = 9.73$ ,  $p = .003$ ), Obstacle ( $F_{1,66} = 12.95$ ,  $p = .001$ ), and Obstacle-Cognitive ( $F_{1,66} = 12.58$ ,  $p = .001$ ) conditions, with the concussed group demonstrating a

significantly greater double support percent in each instance (See Appendix B) . Analyses of the single support percent also revealed significant condition ( $W_5=.69$ ,  $p<.00$ ,  $F_{2,44,160.99}=112.93$ ,  $p<.00$ ) and group ( $F_{1,66}=11.29$ ,  $p<.01$ ) main effects. Post-hoc analyses indicated the single stance percent for each condition was significantly different from all other conditions ( $p's<0.05$ ). Further, the concussed and non-concussed groups differed significantly on the Obstacle ( $F_{1,66}=14.68$ ,  $p=.000$ ) and Obstacle-Cognitive ( $F_{1,66}=12.97$ ,  $p=.001$ ) conditions, whereby the concussed group had a significantly shorter time in single leg stance (see Appendix C).

Analysis of Brooks Spatial Task performance indicated a significant condition main effect ( $F_{2,132}=12.71$ ,  $p <0.00$ ), whereby performance on Cognitive condition ( $6.2\pm1.3$ ) was significantly better than the Walk-Cognitive ( $5.7\pm1.5$ ,  $p=.01$ ) and Obstacle-Cognitive ( $5.5\pm1.6$ ,  $p<.00$ ) conditions. There was no difference in performance between groups ( $p>0.05$ ).

Finally, the Spearman's Rho correlational analyses revealed a number of significant relationships. Relative to the association between the number of previous injuries and percent single leg stance time, significance was noted for the Walk ( $r_s = -0.36$ ,  $p <.00$ ), Walk-Cognitive ( $r_s = -0.34$ ,  $p <.00$ ), Obstacle ( $r_s = -0.45$ ,  $p <.00$ ), and Obstacle-Cognitive ( $r_s = -0.42$ ,  $p <.00$ ) conditions. Similarly, the significant relationships between the number of previous injuries and percent double leg stance time were noted in the Walk ( $r_s = .45$ ,  $p <.00$ ), Walk-Cognitive ( $r_s = .34$ ,  $p =.01$ ), Obstacle ( $r_s = .47$ ,  $p <.00$ ), and Obstacle-Cognitive ( $r_s = .44$ ,  $p <.00$ ) conditions. The correlational analyses conducted on the other variables of interest were all non-significant ( $p's>0.05$ ).

## *DISCUSSION*

There are a number of investigations that have outlined the association between concussion and acute alterations in cognitive and motor control (eg gait and balance) (Broglio &

Puetz, 2008). In general, these deficits are thought to spontaneously resolve within several days of injury (McCrary et al., 2009). Emerging evidence however, has begun to show that individuals with a history of concussion have long term alterations in cognitive functioning. Indeed, concussion history has been associated with increased rates and early onset of depression (Guskiewicz et al., 2007), MCI and dementia (Guskiewicz et al., 2005). It has yet to be reported however, if motor control suffers from the same deleterious effects in the years following concussion.

Thus, this investigation is the first to demonstrate that concussion is associated with chronic decrements to the motor control system. Indeed, our investigation revealed that individuals with a history of concussion, an average of 6.32 years prior, continued to show negative alterations in their gait pattern. In fact, our concussed participants demonstrated slowed walking velocity, increased time in the double leg stance phase, and decreased time in the single leg stance phase of the gait cycle. Collectively, these findings indicate that those with a concussion history employ a more conservative gait pattern, particularly while completing the obstacle avoidance task (ie Obstacle and Obstacle-Cognitive conditions). This investigation was not designed to evaluate the cause for these neuromuscular alterations, but it is evident that these individuals have reduced their time in less stable positions (eg single leg stance), conceivably to maintain the center of mass well within the limits of stability and limit injury risk.

Relative to the existing literature, these findings perpetuate the reported alterations in gait reported in acutely concussed individuals. Chou and colleagues demonstrated that concussed individuals walked significantly slower and with shorter stride lengths than the healthy controls. The concussed participants also had greater medial-lateral motion demonstrating increased instability following injury(Chou et al., 2004). When compared to non-concussed athletes, the

concussed athletes showed deficits in medial-lateral sway and displacement up to 14 days post-injury (Parker et al., 2007). Catena and colleagues (Catena et al., 2007) later employed a dual-task methodology in a population of concussed young adults and found the COM sway of the injured group to be significantly increased in the medial/lateral direction compared to both controls and a non-dual task gait assessment. These findings occurred despite the adoption of a slower and more conservative gait strategy by the concussed population. These findings demonstrate that gait performance differences become more pronounced with the simultaneous completion of a cognitive task in concussed individuals. Changes in stride length and width appear to have resolved at our testing time point, although suppressed gait velocities continued (Appendix D).

Only one investigation has evaluated the effects concussion on motor control beyond the acute injury stage. Using motion capture technology, concussed and non-concussed individuals were evaluated up to 28 days post injury while stepping over short (4cm) and tall (10% body height) obstacles (Catena et al., 2009). The concussed participants demonstrated general recovery within 6 days of injury, but significant group differences in both the medial-lateral COM displacement and displacement velocity within the concussion group moving less and at slower speeds remained at day 28. Testing was not reported at longer intervals. The similarity in adopting a conservative gait strategy to seemingly protect one-self against falls and other injury appears to remain in the following years as evidenced by the data reported here; albeit on a more subtle level.

Significant differences across conditions in gait velocity noted in this investigation were as expected. That is, the participants walked at a progressively slower pace as task complexity increased. Thus, the fastest walk was completed during the flat, no obstacle condition (Walk),

followed by the obstacle walk (Obstacle), flat walk with cognitive task (Walk-Cognitive), and the combined obstacle and cognitive task condition (Obstacle-Cognitive). Changes in double and single leg percent stance followed a similarly predictable pattern. Double percent stance decreased from the Walk and Obstacle conditions as the participants had to step up and over the added obstacles. Addition of the cognitive task however, increased the double percent stance that was reflected in a slower gait velocity.

We employed Brooks Mental task for its known ability to evaluate the visuospatial system and the known association between visuospatial processing and the cognitive-motor functioning in acute concussive injuries(Sosnoff et al., 2008). Although the participants were given no instructions to focus on either the cognitive or gait task, our results would appear to suggest that cognitive performance was sacrificed during the gait assessment. In the absence of group differences, the participants performed best on the Brooks when seated and not completing the gait assessment (Cognitive condition:  $6.2 \pm 1.3$  correct answers), is consistent with other reports ( Ebersbach, Dimitrijevic, Poewe, 1995). Performance significantly declined when the participants were walking (Walk-Cognitive:  $5.7 \pm 1.5$ ) and walking over obstacles (Obstacle-Cognitive:  $5.5 \pm 1.6$ ), but did not differ between the walking conditions. Even with specific direction to maximize cognitive performance in dual-task situations, others have reported healthy young adults will focus on balance at a level sufficient to avoid injury(Siu KC and Woollacott MH 2007). Thus, it appears as though gait parameters are subject to adaptation depending on the attentional demand of the concurrent task(s), possibly explaining the effects of pathological conditions (eg concussion) and gait adaptation with interfering cognitive and motor demands (Ebersbach et al., 1995)

Finally, we conducted a correlational analysis between our variables of interest and the previous number of concussions reported by our participants. These results indicated that as the number of previous injuries increased, there was a decreased time in single leg stance and increased time in double leg stance for all of the testing conditions. These findings support previously reported evidence showing a relationship between the number of concussions and long-term cognitive dysfunction (Guskiewicz et al., 2005). It is not presently known how many injuries lead to clinical gait deficits and our dataset was too small to evaluate this relationship. With growing evidence indicating the long term effects of concussion, future works should attempt to clarify how many injuries result in clinical pathologies.

The structural underpinnings to motor control changes cannot be elucidated by this investigation, but others have examined if the mechanism for motor control alterations is a result of central or peripheral changes. Using TMS, former athletes with concussions 30 years prior demonstrated a suppressed cortical silent period. This finding was supported by evidence of bradykinesia during a rapid arm movement task. These two findings were significantly correlated and suggest that changes in motor control may result from central nervous system alterations and not alterations in the peripheral system (De Beaumont et al., 2009). Central nervous system changes have been identified in a post-mortem evaluation of cerebral tissue from former professional football athletes with a history of concussion. The evaluation revealed neurofibrillary tangles and neuropil threads resulting from  $\tau$ -protein deposits that were associated with cognitive decline (Omalu et al., 2006; Omalu et al., 2005). Thus, if our cohort has undergone these same structural changes, these deposits may have required the recruitment of alternative motor pathways to perform the desired task. This hypothesis has been demonstrated in concussed adults who recruit additional cortical areas, as evidenced by increased blood oxygen level–

dependent (BOLD) signals, while performing normally on cognitive evaluations (Jantzen, Anderson, Steinberg, Kelso, 2004). The alternate motor control strategy would ultimately lead to delayed reaction times that manifest as slowed motor speed (ie velocity) and a propensity for safer movement patterns that limit exposure to potentially injurious situations.

Although our young adult population did not presently appear to be at risk for falls, some have speculated that cerebral insult coupled with the normal aging process may lead to clinical pathologies(Broglio et al., 2009). It is commonly held that aging is accompanied by a decrease in movement speed coinciding with an increase in motor variability and complexity. This change in speed and variability is seen as disadvantageous since it is related to declines in quality of life and morbidity(Nesselroade & Salthouse, 2004). The mechanisms behind these adverse age related changes have been linked to both peripheral and central nervous system changes.

Changes to the peripheral system tied to aging have been described as: increased muscle spindle capsular thickness, decreased muscle spindle diameter, decreased sensitivity of the muscle spindle, a fewer total number of intrafusal fibers, and axonal swelling/expanded motor endplates that may be the result of denervation (Goble, Coxon, Wenderoth, Van Impe, Swinnen, 2009). Additional declines of Ruffini, Pacinian and Golgi-tendon type receptors in both total number and density also results from aging(Morisawa, 1998). In combination, these changes have obvious implications to declining proprioceptive and thus functional ability in an aging population. That is, as an individual ages he/she is less able to generate accurate and reliable motor control to carry out a specific action. Further, the ability to provide accurate motor control feedback declines as a function of impaired afferent receptor decline. To compound the situation, research has indicated that central nervous system declines associated with aging may also affect motor control processes. For example, Dumas and colleagues demonstrated a 40% static

postural control decrease in older adults (mean 71 years) who simultaneously maintained optimal cognitive performance levels on an n-back task (Doumas, Smolders, Krampe, 2008). Further, when a sway-reference platform was utilized while completing the n-back task, there was a 15% decrease in cognitive performance. These findings demonstrate that older adults have limited cognitive resources and must be selective in maintaining optimal cognitive or motor performance. More specifically, age-related declines in the post-central gyrus function are associated with somatosensation (Raz & Rodrigue, 2006). Declines to this area results in other cortical areas being recruited to maintain optimal postural performance to prevent injury (ie falls). If optimal motor control is the primary goal of the individual, then cognitive performance will suffer. However, if these natural declines are coupled with the persistent effects of concussion, the outcome may be an increased risk for falls or other injuries that may result in disabilities and/or decreased quality of life.

### *Limitations*

While the findings presented here appear to align with other investigations showing changes in gait following concussion, they are limited by the self-report of concussion history. This warrants prudence when interpreting results. Ultimately, the implementation of cross-sectional and longitudinal designs will provide the best indication of how concussion may result in persistent changes. The findings here do support investigations of this nature.

### *CONCLUSIONS*

It is evident that the underlying pathophysiology of concussion results in the non-specific impairment of multiple brain regions in the days following injury (Giza & Hovda, 2001). The clinical presentation is an inter-related effect on both neurocognitive function and various aspects of motor control (eg gait and balance). A plethora of research has evaluated these domains

individually (ie neurocognitive *or* static balance) (Broglia & Puetz, 2008) or in combination (ie dual-task) (Catena et al., 2007) with the common link between cognitive and motor function related to visuospatial performance(Sosnoff et al., 2008). This investigation, and a number of investigations prior to ours(Guskiewicz et al., 2007; Guskiewicz et al., 2005), suggests that concussion related neurocognitive deficits are prolonged and persist into later life with the potential to significantly influence work and health status and quality of life (Voisin & Vellas, 2009). Thus, it stands to reason that persistent deficits in motor control may be present in parallel with the previously observed and reported neurocognitive impairments (Sosnoff et al., 2008). In the final analysis, we demonstrated an association between concussion and persistent gait decrements. These changes were evident in both single task and dual task conditions, raising the possibility that these individuals may be at risk for injury under a variety of conditions.

*Appendix A*

**Participant Demographics**

	Concussed (n=28)	Non- Concussed (n=40)
Male	17	20
Female	11	20
Age (yrs)	21	20.72
Height (cm)	173.56	169.19
Weight (kg)	75.05	72.02
Previous # Concussion	2	0
Time Since Injury (yrs)	6.32	N/A

*Appendix B*

**Double Stance Percent**

		Condition 1: No Obstacle / No Mental Task *	Condition 2: No Obstacle / Mental Task	Condition 3: Obstacle / No Mental Task *	Condition 4: Obstacle / Mental Task *
<b>No Concussions</b>	<i>Mean</i>	42.99	49.27	34.36	38.00
	<i>Std. Deviation</i>	6.09	7.45	4.81	5.08
<b>1+ Concussions</b>	<i>Mean</i>	47.80	52.81	39.58	43.25
	<i>Std. Deviation</i>	6.51	7.01	7.16	7.14

\*  $p < .05$

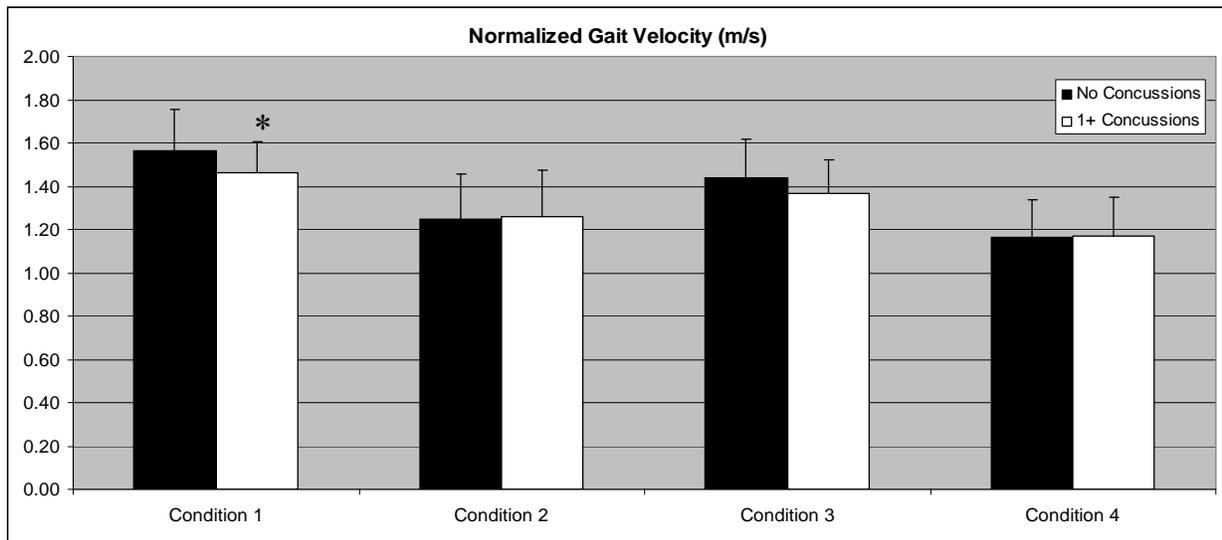
Appendix C

**Single Percent Stance**

		Condition 1: No Obstacle / No Mental Task	Condition 2: No Obstacle / Mental Task	Condition 3: Obstacle / No Mental Task *	Condition 4: Obstacle / Mental Task *
<b>No Concussions</b>	<i>Mean</i>	78.14	75.76	83.14	81.57
	<i>Std. Deviation</i>	3.98	3.72	2.15	2.40
<b>1+ Concussions</b>	<i>Mean</i>	76.39	73.95	80.17	79.07
	<i>Std. Deviation</i>	3.53	3.72	4.20	3.34

\*  $p < .05$

Appendix D



**Figure 1** Normalized gait velocity from the four gait conditions. \*  $p < .05$ , expressing individuals with a history of concussion walked significantly slower.

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