

AN EXAMINATION OF MOTOR AND COGNITIVE RECOVERY FOLLOWING  
CONCUSSION

by

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## DISSERTATION ABSTRACT

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Doctor of Philosophy

Department of Human Physiology

June 2014

Title: An Examination of Motor and Cognitive Recovery Following Concussion

Cognitive and motor impairments have been identified as signs following a concussion which may compromise the performance of everyday tasks or physical activities. However, little work has been done in the adolescent population using laboratory based measurements of attention or balance control to identify recovery from concussion. Therefore, the purpose of this dissertation was to prospectively and longitudinally observe how individuals who have sustained a concussion recover on measures of attention and gait balance control in comparison to individually matched, healthy control subjects from within 72 hours of injury up to two months following injury.

Individuals were identified as sustaining a concussion by healthcare professionals and began participation in the study within 72 hours of injury. They then returned to the laboratory at approximately 1 week, 2 weeks, 1 month, and 2 months post-injury. Control subjects were individually matched by sex, age, height, and weight and tested in similar time increments. Attentional abilities were measured via multiple computerized testing assessments, and gait balance control was measured with whole-body motion analysis.

The results indicated that following concussion, adolescents display deficits in

conflict resolution ability, task switching ability, and gait balance control during dual-task walking for a time period of up to two months following injury in comparison to a matched control group. During dual-task walking, the complexity of the cognitive task performed may affect adolescents with concussion to a greater degree than matched control subjects. Adolescents also displayed regressions to gait stability recovery following their return to physical activities. Finally, adolescents with concussion displayed greater gait balance control deficits than young adults with concussion throughout the two months of testing when each group was compared to a respective healthy control group.

Results from this dissertation indicate that concussion affects cognitive and motor functions in adolescents, who display deficits throughout two months post-injury. Computerized attentional tests and dual-task dynamic balance control assessments represent a multifaceted approach to concussion management and may provide another assessment battery for healthcare professionals to utilize in order to identify recovery following concussion.

This dissertation includes previously published/unpublished co-authored material.

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## CHAPTER I

### GENERAL INTRODUCTION

#### Background and Significance

The Centers for Disease Control and Prevention have previously identified traumatic brain injury (TBI) as a serious public health problem in the United States (89). As the incidence of such injuries has steadily increased over the past 15 years (95), there has been an increasingly growing concern for individuals who suffer a brain injury, particularly those 15 years of age or younger, as they represent a large percentage of the over 1 million TBIs resulting in emergency room visits every year (89, 120).

Concussion has been identified as a type of TBI, often referred to as a type of mild traumatic brain injury (mTBI), and remains one of the most complex and controversial injuries that sports medicine professionals encounter (14, 46). It may occur from forces that are applied directly or indirectly to the skull, resulting in a rapid acceleration or deceleration of the brain (14, 112). Most recently, it has been defined as a trauma-induced alteration in mental status that may or may not involve loss of consciousness (14). Such alterations to mental status are thought to occur due to ionic and metabolic disturbances within the brain (60), however the time duration required to recover fully from injury remains unknown. Long-term repeated head impacts have been implicated in mild cognitive impairment (64) and may potentially induce pathological changes to the brain observed upon post-mortem analysis (116). Furthermore, recent evidence from post-mortem analysis has indicated that even a single concussive event may promote the accumulation of neurofibrillary tangles in the brain (82).

Concussions are complex injuries influenced by a variety of factors (58), and the duration of time required to achieve complete recovery following a single concussion remains unknown. Previous reports on recovery duration from a single concussion range from 7 days (10) to many years post-injury (9). Furthermore, it has been demonstrated that neurocognitive deficits related to a concussive event have been shown to persist beyond the time when patients report symptoms have resolved (15), underscoring the need for objective ways to measure how individuals recover from the injury (141). However, many investigations rely on cross-sectional, retrospective data (50, 103) or fail to follow individuals with concussion for more than two weeks after the injury (35, 55, 108). No investigations have been reported, thus far, that systematically examine the way concussion affects gait or cognitive abilities in a prospective and longitudinal manner through a time period of two months post-injury.

### Goals and Specific Aims

The overall goal of this dissertation study is to prospectively and longitudinally examine the effects of concussion on attention and dynamic balance control in adolescents. As previous literature has often focused on adult populations (73), the adolescent age group has been largely overlooked (73) despite being a physically immature population, vulnerable to the effects of head trauma and potentially recovering differently than young adults (119).

Within the context of this dissertation study, five specific aims were identified to investigate.

**Aim 1:** To determine whether differences exist between adolescents with concussion and matched, healthy control subjects on tests of attention and task switching throughout the two-months following injury.

Recent evidence has identified attention (71) and task switching (106) impairments following concussion in young adults through the use of laboratory based computer testing protocols. Although head trauma in adolescents has been linked with executive dysfunction (74), little research has been conducted employing laboratory-based measurements of attention and task switching in this age group. A longitudinal analysis of the recovery patterns of these measures among adolescents is central to the understanding of the effects of concussion across the age spectrum.

**Aim 2:** To determine if differences between adolescents with concussion and healthy control adolescents are present in single-task and dual-task gait balance control within 72 hours of injury and throughout the two months post-injury.

Disruptions of gait function after concussion have been previously reported in adults (50, 103, 128), but little is known about gait disturbances in adolescents post-concussion. Difficulties reported in walking while performing a concurrent task may be due to an alteration of attentional resources (28, 168). This suggests that measures of gait balance control under divided attention conditions may be a sensitive indicator of functional impairment from concussion and be a variable of interest in monitoring recovery (137).

**Aim 3:** To assess how secondary task complexity affects gait balance control throughout the two months following concussion for adolescents with concussion and matched healthy control subjects.

One method to examine disturbances to motor and cognitive function following concussion is the use of a dual-task paradigm (28, 103, 128). However, how the complexity of the secondary task, in such a paradigm, affects gait balance control has not yet been reported. An examination of gait balance control under conditions of varying complexity following concussion can help to better understand the utility and sensitivity of this paradigm in the assessment and recovery of adolescents who sustain a concussion.

**Aim 4:** To observe how resumption of pre-injury levels of physical activity affects recovery from concussion in adolescents, through measurements of gait balance control, cognition, and symptom severity.

Previous work has identified gait balance control impairments under dual-task conditions following concussion (28, 128). Additionally, Parker et al. (2006) reported a significant increase in medial-lateral displacement from a two week assessment to a one month time point following concussion in a group of young adults who each returned to physical activities within 2 weeks of the injury (128). Thus, it was suggested that motor abilities may not be fully recovered prior to returning to activity and this gait stability regression may potentially identify motor system impairments and possible vulnerability to further injury. Despite this evidence, the effect of the return to physical activities on gait function has not yet been investigated in a group of adolescents returning to sport activities. Thus, an examination of how the resumption of pre-injury physical activities affect concussion recovery on measures of gait balance control during dual-task walking, symptom severity, and cognition may help to elucidate ways to effectively monitor recovery.

**Aim 5:** To determine whether differences between adolescents and young adults with concussion exist on measurements of gait balance control during dual task walking, initially after injury and throughout the two months post-injury.

Current treatment protocols suggest that after a concussion, the management of younger individuals should occur in a more conservative manner than adults (72, 112), however it has also been reported that recovery in individuals aged 15 years and younger has not yet been adequately studied (73). While each of the previous four aims have focused on motor and cognitive recovery from concussion in adolescents, there is a need to better understand how concussion affects these functions across an age spectrum. Thus, an examination of gait balance control following concussion in a group of adolescents and young adults in reference to a matched group of control subjects may help to identify the effect of age on post-injury recovery.

### Hypotheses

The first hypothesis for this dissertation study was that adolescents with concussion would be affected in their ability to resolve conflict, switch between tasks, and walk while completing a secondary task to a greater degree than matched control subjects for a time period of one to two months post-injury. The secondary hypothesis was that the return to physical activity timing may affect the recovery of these abilities and that younger individuals may demonstrate greater effects from a concussion.

## Flow of the Dissertation

This dissertation is structured in a journal format. Chapters II through VI represent individual manuscripts which have been published, are currently in press, or have been submitted for publication in peer-reviewed scientific journals.

Chapters II-V describe two month, prospective and longitudinal investigations on the recovery of adolescents who sustained a concussion on a number of variables. For each variable, the results for those who have sustained a concussion are compared to those of individually matched, healthy control subjects. Subjects with concussion were initially tested within 72 hours of injury and then tested again at approximately one week, two weeks, one month, and two months post-injury. Control subjects adhered to the same timeline and completed the same protocol as subjects with concussion. The variables associated with each chapter are identified below:

Chapter II – Measures of conflict resolution and task switching

Chapter III – Gait balance control under single-task and dual-task conditions

Chapter IV – Gait balance control under dual-task conditions of varying complexity

Chapter V – All variables previously identified relative to the date of return to pre-injury levels of physical activity

Chapter VI – A comparison between adolescents with concussion and young adults with concussion on measures of gait balance control under dual-task conditions

Chapter VII provides a general summary and recommendations for future research, followed by appendices which include a review of concussion-related

literature and informed consent forms used in the studies, and finally a list of references.

Each of the five studies included in the dissertation (Chapter II – Chapter VI) include co-authored material. Chapter II, Chapter III, and Chapter IV have been published or accepted for publication in the following journals, respectively: *Medicine and Science in Sports and Exercise*, *Archives of Physical Medicine and Rehabilitation*, and *Experimental Brain Research*. Chapter V and Chapter VI have been submitted for publication to peer-reviewed journals and are currently in review.

## CHAPTER II

### STUDY 1: EFFECTS OF CONCUSSION ON ATTENTION AND TASK SWITCHING ABILITY IN ADOLESCENTS

This work was published in volume 45, issue 6, of the journal *Medicine and Science in Sports and Exercise* in 2013. David Howell contributed to the concept of the study, recruited subjects, coordinated and supervised data collection, wrote analysis software, performed initial data analysis and statistical analysis, and prepared the initial manuscript. Ulrich Mayr and Paul van Donkelaar contributed to the conception of the study, provided editorial support, and provided expertise on the study data collection software. Louis Osternig and Li-Shan Chou contributed to the concept of the study, the analysis and interpretation of the data, and critically reviewed and revised the manuscript.

#### Introduction

The Centers for Disease Control and Prevention have described brain injury as a silent epidemic (89) which suggests that mild traumatic brain injury (mTBI) has become a public health problem, the magnitude and impact of which are underestimated by current surveillance systems. Many of the mTBIs that occur in young adults and adolescents take place in the context of sport activities (85) and thus, fall into the category of sports-related concussion. It has been found that deficits from this injury may last longer than those reported by the patient and may be present even after the return to unrestricted activity (15, 83, 108) suggesting that current clinical assessment tools may lack sufficient sensitivity to accurately track functional recovery.



Executive function has classically been defined as the capacity to flexibly plan purposeful behavior (94) and is considered to be responsible for the synthesis of external stimuli and preparation for action (99). Attention processes are believed to be important elements of executive function (3) as well as tasks requiring deliberate attention including decision making, troubleshooting, a novel sequence of action, and tasks considered technically difficult (125). These functions can be tested by using a variety of laboratory-based tasks in which an individual must generate one of two or more responses in a context-dependent manner. Performance on such tasks has been shown to be deficient in college age students who have suffered a concussion for up to one month after the injury (71). Previous literature suggests that tests which focus on executive functions in individuals recovering from mild to moderate TBI may be useful in predicting outcome from injury (74).

Although the adolescent brain has not yet reached full maturation (39, 98, 126) and is in a period of rapid development from approximately 14-16 years old of age (3, 56), few studies have focused on the long term consequences of concussion in adolescents. In a retrospective study assessing sport concussions in children, adolescents and adults, Baillargeon and colleagues (4) reported that adolescents displayed persistent neurophysiological deficits that were present at least 6 months following a concussion and were more sensitive to the consequences of concussion than in adults. The adolescent age group has been reported to be vulnerable to the effects of concussion due to the continued development of the frontal region of the brain (97), which is responsible for working memory and executive function. A head injury during this critical development time could result in deleterious effects on these cognitive components (4).

Because executive function is considered to encompass the highest levels of human functioning (42) and attention processes are considered to play important roles in the control of action (125), the monitoring of these cognitive elements in a population particularly vulnerable to the effects of concussion is warranted.

Recognizing how such cognitive functions are affected by and recover after concussion in adolescents can help medical personnel better identify incomplete recovery, which is a predictor of recurrence of brain injury (67). This information may provide much needed additional data for the reintegration to pre-injury levels of mental and physical activities. Therefore, the purpose of this study was to prospectively and longitudinally examine measures of attention and executive function in a cohort of adolescents who have sustained a concussion and healthy, matched control subjects within a 72 hour acute post-injury interval and over the subsequent two months post-injury.

The hypothesis of this investigation, based on prior research in young adults, was that adolescents would be significantly affected by concussion on tests of attention and executive function for up to one month post-injury when compared to a healthy group of age-matched control subjects who underwent the same testing timeline and protocol.

## Methods

### *Participants*

Forty high school students participating in school sports at three local high schools (36 males/4 females) were identified and recruited for testing. Twenty of the participants were identified by specialized health professionals (certified athletic

trainer/physician) as suffering a concussion consequent to sport participation.

Concussion was defined according to the 3<sup>rd</sup> International Statement on Concussion in Sport as an injury caused by a direct blow to the head, face, neck or elsewhere in the body with an impulsive force transmitted to the head resulting in impaired neurologic function and acute clinical symptoms (111). Each subject who sustained a concussion in the study was matched with a healthy control subject (n= 20) by sex, height, mass, age, and sport. Prospective control subjects were identified by certified athletic trainers at the high school from which the matched concussion subject was a student. Matching criteria were confirmed at the laboratory test site.

Each subject with a concussion was removed from the injury site on the day of injury and did not return to pre-injury levels of physical activity until cleared by a physician in accordance with state law. Exclusion criteria for concussion and control subjects included: 1) lower extremity deficiency or injury which may affect normal gait patterns, 2) history of cognitive deficiencies, such as permanent memory loss or concentration abnormalities, 3) history of three or more previous concussions, 4) loss of consciousness from the concussion lasting more than one minute, 5) history of attention deficit hyperactivity disorder, or 6) a previously documented concussion within the past year. Individuals with a history of 3 or more previous concussions were ineligible to participate to ensure, to the extent possible, the exclusion of subjects suffering from chronic mTBI. Subjects who suffered loss of consciousness for more than one minute were excluded from participation in the study because that sign is believed to play a role in concussion management modification (111).

Prior to data collection, the institutional review board reviewed and approved the protocol of the current study. All subjects and parent/guardian (if under the age of 18) provided informed consent. Permission was also granted by the respective school districts to conduct testing with student participants.

A prospective, repeated measures design was employed in which each subject reported to the laboratory and was tested within 72 hours of sustaining a concussion as well as on four subsequent testing days at the following time increments: one week, two weeks, one month, and two months post injury. Control subjects were similarly tested according to the same time schedule. The Attention Network Test (ANT) (53) and the Task-Switching Test (TST), adapted from Mayr and Bell (105), were administered separately and individually to each study participant in a visually enclosed space free from distracting noise and other people. The components of cognitive function each test measures have been shown to be sensitive to the effects of concussion (20, 71). Additionally, in order to better understand the clinical presentation of each subject, a concussion symptom checklist was administered which assessed 22 symptoms on a 6 point Likert scale adapted from McCrory et al. (111).

#### *Attention Network Test*

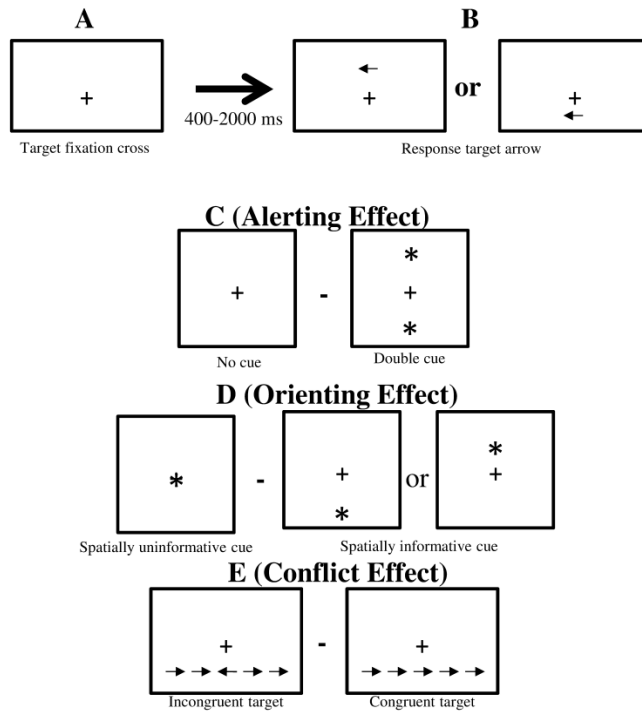
The ANT was originally designed to evaluate abnormalities arising in cases of brain injury, stroke, schizophrenia, and attention deficit disorder (53). It probes the efficiency of three distinct components of attention: alerting (alerting effect), spatial orientation (orienting effect), and executive function (conflict effect) by assessing the relative change in reaction time (RT) to differing precue and stimulus configurations (53). Event-related functional magnetic resonance imaging (fMRI) has been used to

explore the brain areas involved in the three attention systems targeted by the ANT (52). The results suggested that the functional contrasts within the ANT tended to differentially activate three separable anatomical networks related to the components of attention. The conflict effect has been shown to be significantly affected by mTBI up to one month post-injury and the orienting effect has been shown to be affected within the first two days post-injury in young adults (71), but these effects have yet to be systematically studied in adolescents suffering from concussion.

Over the past 10 years, versions of the ANT have been used in over 60 publications dealing with a wide range of topics and methods including: development, neuroimaging, pharmacology, genetics, psychiatric disorders, brain damage, and individual differences (81). Recently, Ishigami and Klein (81) tested the reliability of the ANT on healthy young adults over ten testing sessions. They observed learning effects over the first few sessions for the executive component (conflict effect) and reported that reliability improved as more sessions were included in the analysis. Between sessions 1 and 2 they found correlations of -0.02, 0.57 and 0.86, and when combining sessions 1-10 (using a modified split-half correlation analysis) of 0.80, 0.65 and 0.93 for the alerting, orienting and executive components, respectively. It was concluded that the ANT was robust after multiple sessions and suitable for applications requiring repeated testing. Due to the noted practice effects it was suggested that controls are warranted in some designs.

In the ANT, the subject fixates on a cross in the center of a computer screen and responds as quickly as possible by pressing one of two arrow keys indicating the direction (left or right) of a central arrow presented either directly above or below the

cross (Figure 1A & 1B). Four dependent variables of interest were used in further analysis. The Grand Median was calculated as the median RT of all accurate trials completed. The other three (alerting effect, orienting effect, and conflict effect) were calculated as median RT differences across different test conditions. The alerting effect is examined by determining the RT difference between trials in which a warning cue (asterisk) precedes the arrow stimulus vs. trials in which the warning cue does not precede the arrow stimulus (Figure 1C). The orienting effect is examined by the RT difference between trials in which the warning cue indicates the location of the arrow stimulus (above or below the fixation cross) vs. trials in which the warning cue does not provide such spatially relevant information (Figure 1D). Finally, the conflict effect is assessed by the RT difference between trials in which the arrow stimulus is accompanied on either side by two congruent flanker arrows (i.e. arrows pointing in the same direction) vs. trials in which the arrow stimulus is accompanied on either side by two incongruent flanker arrows (i.e. arrows pointing in the opposite direction; Figure 1E). Thus, the effect is measured by the RT difference between the two conditions presented for each of the three networks (alerting, orienting and conflict). A greater RT difference score between groups/testing days, indicates poorer performance on that attention network. Participants first completed a series of 24 practice trials with visual accuracy feedback; they then completed two blocks of experimental trials made up of 96 trials (4 precue conditions x 2 target locations x 2 target directions x 3 flanker conditions x 2 repetitions) for a total of 192 experimental trials.



**Figure 1:** Attention Network Test: the sequence of events during trials. Subjects focus on the fixation cross and are instructed to respond by pressing the keyboard arrow (left or right) corresponding to the direction of a target arrow when presented directly above or below the cross (A and B). The asterisk is a precue (C and D) which gives information about when (alerting) or where (orienting) the target will appear. Flanker arrows (E) may be presented in configurations which test conflict and non-conflict effects.

### *Task Switching Test*

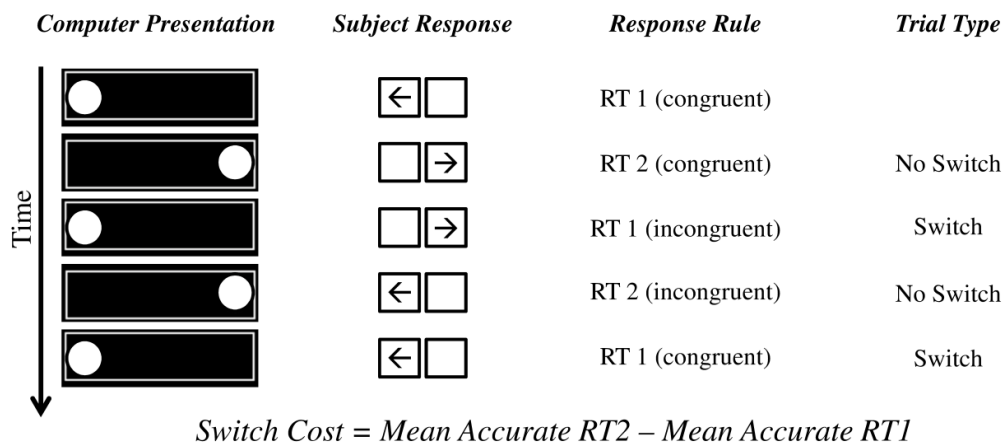
The TST uses a paradigm that specifically tests the ability to flexibly switch between competing task or stimulus-response rules (142). The primary dependent variable is the switch cost, which is the difference score between the response time from trials on which the task changes (i.e., switch trials) and trials on which the task stays the same (i.e., no-switch trials). Switch costs across different task pairs correlate highly with each other (105, 122), suggesting that these costs (a) can be assessed reliably and (b) are independent of the primary task. Further, numerous studies have found that switch costs reflect an executive function that is largely independent of other executive abilities, such

as the resolution of conflict or working memory (122). Previous work has found that task-switching ability is highly sensitive to mTBI in adults (20), but has not been studied in adolescents with concussion. The task-switching paradigm has been used to study executive functions in the context of cognitive development, cognitive aging, and brain imaging (121). Additionally, task switching has been used in studies of a wide array of clinical disorders, including attention deficit hyperactivity disorder, Parkinson's disease, and frontal lobe injury (121). The specific paradigm employed within the current study design has been documented as a valid way to examine executive functioning and is reliable across testing sessions (142). Rogers and Monsell (1995) demonstrated that extra practice did little to increase subject performance when repeat testing occurred, indicating test stability between testing days (142).

For the current TST, subjects were required to switch between responding congruently and incongruently to the position of a visual stimulus on every 2<sup>nd</sup> trial in a sequence (105). The subjects responded to the position of a circle presented in a horizontally configured rectangular box (Figure 2) by pressing the right or left arrow key on a standard computer keyboard as quickly and accurately as possible. In the congruent case the subject indicated the left or right position of the circle by pressing the corresponding arrow key. In the incongruent case, the subject pressed the opposite key (i.e., left arrow key for right target and vice-versa). The subject alternated between congruent and incongruent responses on every 2<sup>nd</sup> trial throughout the sequence of four blocks of 52 trials (208 total trials). If an incorrect response was generated, a visual display was presented to remind the subject which rule (congruent or incongruent) was required to respond correctly. The dependent variable of interest was the “switch cost.”



This is defined as the difference in RT between “stay” trials, in which the subject did not switch from responding congruent or incongruently (or vice-versa), and “switch” trials, in which the subject did switch from responding congruently to incongruently (or vice-versa).



**Figure 2:** Task Switching Test: the sequence of trials. The subject responds to the position of the circle within the rectangle by pressing the arrow key in either a congruent or incongruent manner, alternating every two trials. The switch cost is calculated as the mean accurate response time difference of trials which repeat congruent/incongruent responses (no switch) and those which switch between congruent/incongruent responses (switch). The performance differences between trial types are commonly used as measures of executive function ability.

Therefore, the switch cost is a measurement of the difference in response time during trials where the rule switched compared with trials where the rule stayed the same. A higher switch cost indicates greater difficulty in adhering to the congruent/incongruent rules. Only trials in which an accurate response was generated were included in the calculation of the switch cost.

### *Statistical Analysis*

Data were analyzed by two-way, mixed effects analyses of variance to determine the effect of group (concussion vs. controls), time (72 hours, one week, two weeks, one month, and two months), and the interaction effects on each of the dependent variables (alerting, orienting, and conflict effects and switch cost). For all omnibus tests, significance was set at  $p < .05$ . Follow up pairwise comparisons were then examined using the Bonferroni procedure to control Family-Wise Type I Error. All statistical analyses were performed with SPSS version 20 (SPSS Inc, Chicago, Illinois).

### Results

The concussion subjects were tested within 3 days of injury (mean  $2.15 \pm 0.75$  days). After the initial testing took place, each participant returned for testing in the following increments (mean  $\pm$  SD): 8 ( $\pm 1.8$ ) days, 17 ( $\pm 3.6$ ) days, 30 ( $\pm 2.6$ ) days, and 59 ( $\pm 3.5$ ) days following the injury. Control subjects began participation during the same sport season as their matched concussion subject. After the initial testing session the control subjects returned for testing in the following time increments: 8 ( $\pm 2.1$ ) days, 16 ( $\pm 4.5$ ) days, 30 ( $\pm 3.7$ ) days, and 57 ( $\pm 6.4$ ) days after the initial testing session. No significant demographic group differences were observed between the concussion and the control group (Table 1). In one case, a direct sport match was not obtained.

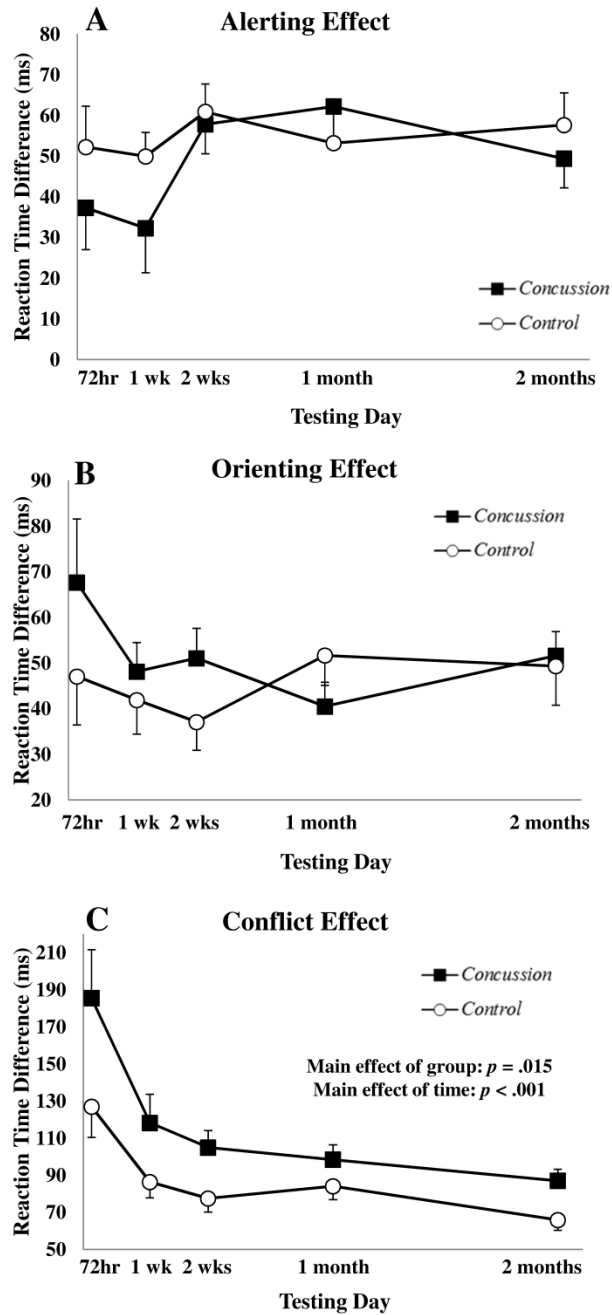
Evaluation of clinical symptoms between the concussion and control groups revealed a significant time by group interaction ( $p < .001$ ). Follow-up pairwise comparisons revealed that concussion subjects exhibited a significantly higher symptom score than control subjects at the following time points (mean [ $\pm$  SD];  $p$  value): 72 hour

(concussion = 43.0 [ $\pm$  25.1], control = 4.3 [ $\pm$  4.2];  $p < .001$ ), one week (concussion = 30.8 [ $\pm$  25.2], control = 2.5 [ $\pm$  2.7];  $p < .001$ ), and two week (concussion = 24.1 [ $\pm$  22.1], control = 4.1 [ $\pm$  8.9];  $p = .001$ ). Those differences were no longer statistically significant at the one month (concussion = 12.6 [ $\pm$ 14.3], control = 3.1 [ $\pm$ 4.5];  $p = .010$ ) or two month (concussion = 11.3 [ $\pm$ 19.8], control = 4.2 [ $\pm$ 6.3];  $p = .149$ ) time points, indicating symptom resolution for concussion subjects on average between the two week and one month testing period.

**Table 1:** Subject characteristics (group mean  $\pm$  SD).

<b>Characteristic</b>	<i>Concussion Subjects</i>	<i>Control Subjects</i>
Age (year)	15.3 (1.3)	15.6 (1.0)
Sex (M/F)	18/2	18/2
Height (cm)	173.7 (6.4)	173.4 (8.1)
Mass (kg)	74.8 (16.6)	70.7 (13.6)
Sport	Football: 15 Soccer: 3 Volleyball: 1 Wrestling: 1 Basketball: 0	Football: 15 Soccer: 2 Volleyball: 1 Wrestling: 1 Basketball: 1

Analysis of the Grand Median component of the ANT revealed a significant group x time interaction ( $p = .001$ ). However, follow-up pairwise comparisons indicated that there were no significant differences between groups at any time point. Evaluation of the alerting effect of the ANT demonstrated no significant differences between groups or testing days, and no interactions were present (Figure 3A; interaction effect  $p = .516$ , main effect of group  $p = .323$ , main effect of time  $p = .223$ ).

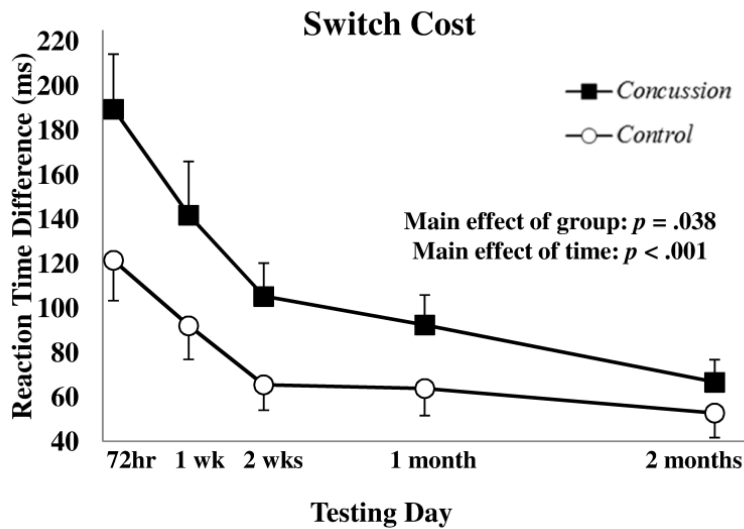


**Figure 3:** Mean (+SE) for performance on the ANT across the two month testing period: (A) alerting effect, (B) orienting effect, and (C) conflict effect. Main effects of group and time were observed for the conflict effect, while no significant main effects or interactions were found for the alerting or orienting effects.

Similarly, evaluation of the orienting effect of the ANT revealed no differences between groups or testing days, and no interactions were present (Figure 3B; interaction effect  $p = .258$ , main effect of group  $p = .236$ , main effect of time  $p = .266$ ). Analysis of the ANT conflict effect revealed a significant main effect of group (Figure 3C;  $p = .015$ , effect size = .192, mean difference value = 34 ms), with the concussion group showing a significantly greater RT difference than controls, indicating a greater conflict effect. A main effect of time was also found to be significant ( $p < .001$ ), but with no significant interaction between group and time ( $p = .308$ ).

Similar to the conflict effect, the TST switch cost (RT difference) was greater for the concussion group ( $p = .038$ , effect size = .125, mean difference value = 38 ms). A main effect of time ( $p < .001$ ; Figure 4) was also found to be significant, but with no significant interaction between group and time ( $p = .253$ ).

Observation of the recovery curves for the conflict effect and switch cost data revealed improving scores over the first two weeks of testing for the control subjects suggesting a practice/learning effect on these measures (Figure 3C and Figure 4). Similarly shaped recovery curves were evident for the concussion subjects over the same time period; however their scores remained significantly different from the controls throughout the testing period.



**Figure 4:** Mean (+SE) for the switch cost, the evaluation of executive function by the TST: The mean RT difference between a switch trial and a no-switch trial for individuals with concussions and controls across the two month time period of testing is displayed. Main effects of group and time were observed for this measurement.

### Discussion

This investigation was a longitudinal analysis of two cognitive tests which examined how attentional and task switching abilities were influenced by concussion in adolescents. The results demonstrated that executive functions, assessed in both the ANT and TST was disrupted in adolescents with concussion for up to two months after the injury when compared to a healthy cohort of matched control subjects. By contrast, the alerting and orienting components of attention were not affected by concussion.

The ANT conflict effect appeared to be considerably disrupted by concussion as the injured group had difficulties ignoring irrelevant information contained in the incongruent target configurations. This resulted in significantly longer reaction time scores than controls for this measure throughout the testing period. These findings are consistent with those of Halterman and colleagues (71) who found the ability to focus

while ignoring irrelevant but conflicting stimuli was impaired up to 1 month following concussion in young adults when compared to matched controls. In the present study, this impairment was evident in the adolescent concussion group for up to two months post-injury. This impairment was observed for an extended period of time when compared to results from the clinical symptom inventory, as the resolution of symptoms typically occurred between the two week and one month following injury.

Previous reports indicate that the ANT orienting effect was negatively affected in young adults with concussion during the first 48 hours after injury (71). In contrast, the present study detected no differences between groups at any time points for the orienting effect. This may be due to a difference in subject age, or that the current study included those whose initial testing time was up to 72 hours after injury, thus extending the amount of potential initial recovery from injury. However, the difference between healthy and concussion subjects at 72 hours post-injury appears to be similar to those previously reported, however statistically insignificant. Additionally, the lack of any differences between groups or across testing days for the alerting effect is consistent to previous findings in young adult subjects (71). The lack of significant differences between groups in both the orienting and alerting effects may also indicate that no pre-existing attentional deficits were present between healthy and concussion subjects.

Previous literature identifies the anterior cingulate cortex and prefrontal cortex regions of the brain as the areas responsible for conflict resolution (51). The anterior cerebral structures are believed to play a role in the ability to focus attention on relevant stimuli while filtering out extraneous information (152, 153). As these frontal regions of the brain are among the last to develop (150), this region of the adolescent brain may be

susceptible to concussion and deficits may last longer in this population than older age groups (4).

In the TST, the reaction time cost of accurately switching from one task to another was significantly greater for the concussion group than the control group throughout the two month testing period. Task switching tasks have previously been shown to probe executive functions by requiring subjects to flexibly plan responses in a context-dependent manner (107). Given that efficient and accurate performance of motor skills involves reaction to and behavior produced from multiple stimuli occurring simultaneously, the task-switching paradigm may provide useful information on the demands of changing internal cognitive configurations (105), which must be addressed during multi-tasking endeavors, such as in academic, job-related, and sport activities.

Executive functions have been considered to be responsible for the synthesis of external stimuli and preparation of action (99) and individuals with mTBI often struggle to maintain or appropriately allocate their attentional resources while performing one or more concurrent tasks (31, 32, 34, 149). The results of this study suggest that tests which isolate executive components of attention, such as conflict resolution or task switching, are sensitive to the effects of concussion in adolescents and reveal cognitive deficiencies that may last for at least two months after concussion. These data suggest that executive function testing may provide a highly useful assessment to identify disturbances and track recovery following concussion for the adolescent population. As task switching and conflict resolution are central to any activity which involves distribution of attention, this type of testing may help to understand how well an individual will respond to such a demand when required to do so.



In this study, both groups of subjects displayed improvements in the ANT conflict effect and TST switch cost across the two month testing period indicating that performance on both tasks got better with practice and/or learning. Similar practice effects were observed over the first few days of testing on the ANT conflict effect by Ishigami and Klein (80, 81), and as a consequence, they noted the need for a control group in some designs. Given the significant between group differences and the lack of an interaction between the concussion and control groups across the testing sessions, these tasks appear to remain sensitive to disruptions induced by concussion for up to two months post-injury.

The strict subject inclusion criterion related to recruiting and beginning testing within 72 hours following injury was a limitation of this study as it resulted in the loss of some potential concussion subjects who were unable to enroll in the study as they could not report for testing within this initial 72 hour time frame. However, there was no attrition of any of the 40 subjects over the course of testing. This study was also limited in that no subject baseline data were reported. The inclusion of individually matched healthy control subjects to which the concussion group was compared for the same testing periods countered this limitation to some extent. Although all injured subjects were considered to have sustained a mild traumatic brain injury (concussion) as defined by the 3<sup>rd</sup> International Statement on Concussion in Sport (111), there undoubtedly was variability in the extent of the injury possibly due to different mechanisms of injury. This variability was mitigated by the exclusion criteria.

## Conclusion

On the basis of the findings of this study, adolescents who have sustained a concussion appear to have difficulty recovering conflict resolution and task switching abilities after injury and may require extended recuperation before full recovery is achieved. Evaluations focusing on such abilities can be useful additions in the assessment and follow-up after head injury.

## Bridge

Chapter II summarized how adolescents who sustain a concussion appear to have difficulty in recovering conflict resolution and task switching abilities after injury and thus may require extended recuperation time before full recovery is achieved. The tasks used in this study were well-validated and relied on computerized administration in an isolated and quiet condition. Next, it is crucial to understand how these impairments to attention following concussion affect the performance of motor and cognitive activities performed simultaneously through the use of a dual-task paradigm. From this information, we may be able to identify how both systems are affected following injury and if completing a cognitive task while walking affects gait balance control for an extended period of time compared with a control group in a similar time increment testing approach as Chapter II.

## CHAPTER III

### STUDY 2: DUAL-TASK EFFECT ON GAIT BALANCE CONTROL IN ADOLESCENTS WITH CONCUSSION

This work was published in volume 94, issue 8, of the journal *Archives of Physical Medicine and Rehabilitation* in 2013. David Howell contributed to the concept of the study, recruited subjects, coordinated and supervised data collection, wrote analysis software, performed initial data analysis and statistical analysis, and prepared the initial manuscript. Louis Osternig and Li-Shan Chou contributed to the concept of the study, the analysis and interpretation of the data, and critically reviewed and revised the manuscript.

#### Introduction

Recently, reports of increased concussion occurrences may have resulted in a greater awareness of their effects and in the enactment of laws in many states to protect individuals from repeat injury (95, 157). It is estimated approximately 1.6 to 3.8 million concussions occur annually as a result of sport participation (90), many of which are sustained by high school aged students (58, 101). This suggests the adolescent population is particularly exposed to brain injury. Much of the current research on adolescent concussion has focused on neuropsychological function (36, 91, 118), reported to be the cornerstone of concussion assessment (110). However, previous investigations indicate concussion is a multi-dimensional injury, which affects not only neuropsychological processes but also body movement control, and that these two

functions are associated (148). Consequently, it has been recently suggested that using multiple measures to diagnose and manage concussion may help to more thoroughly monitor injury recovery (136).

Disruptions of gait function after concussion have previously been reported, although primarily in the adult population. Martini et al (2011) observed those with a history of concussion adopted a more conservative gait pattern, documented by decreased walking speed, increased double leg support time and decreased single leg support time compared with control subjects during dual-task walking (103). Additionally, Fait et al (50) have reported that despite no differences on measurements of symptoms and neuropsychological tests between subjects with concussion and control subjects, individuals with concussion still displayed altered walking performance during dual-task conditions compared with control subjects at an average of 37 days post-injury. Furthermore, other work has identified disruptions to dynamic balance control during dual-task walking for up to 28 days following injury in young adults (127). As these reports have elucidated information regarding recovery from concussion in the adult population, no studies, to our knowledge, have examined recovery of gait balance parameters specifically in the adolescent population. Thus, examining dynamic balance control longitudinally after concussion in adolescents can provide important information regarding its long-term effects.

It has been postulated that difficulties in locomotion while performing a concurrent cognitive task (dual-task) may be due to a reduction in attentional resources (28, 29, 168). The introduction of a cognitive task during walking allows for the simultaneous measurement of motor and cognitive performance, two domains commonly

reported to be affected by concussion (16, 27, 123). The Stroop test, performed during walking, in particular provides information about conflict resolution by eliciting responses in a congruent or incongruent manner, a method which has previously been shown to be significantly affected by concussion (30, 71). Hence, a dual-task paradigm utilizing the Stroop test represents a method to probe how an individual will perform when engaging in the regular activities of daily living during recovery from a concussion.

Therefore, the purpose of this study was to prospectively and longitudinally examine gait balance control during single and dual-task walking in adolescents with concussion within a 72 hour acute post-injury interval and over the subsequent two months post-injury. It was hypothesized that walking while performing a concurrent secondary task would induce inordinate disruptions to gait performance in adolescent subjects with concussion when compared to matched healthy control subjects.

## Methods

### *Participants*

Forty high school students participating in school sports at three local high schools (36 males/4 females) were identified and recruited for testing. Twenty of the participants were identified by health professionals (certified athletic trainer/physician) as suffering a concussion consequent to sport participation. Concussion was defined according to McCrory et al (111) as an injury caused by a direct blow to the head, face, neck or elsewhere in the body with an impulsive force transmitted to the head resulting in impaired neurologic function and acute clinical symptoms. Symptoms resulting from the injury were assessed using a 22 symptom inventory adapted from McCrory et al (111).

The total range of the inventory was 0 to 132 with each symptom ranked 0 to 6 via a Likert scale. Each concussion subject in the study was matched with a healthy control subject (n= 20) by sex, height, mass, age, and sport. Prior to data collection, the institutional review board reviewed and approved the protocol of the current study. All subjects and parent/guardian (if under the age of 18) provided informed consent. Permission was also granted by the respective school districts to conduct testing with student participants.

All subjects identified as suffering a concussion were removed from the injury site on the day of injury and did not return to pre-injury levels of physical activity until cleared by a physician in accordance with state law. Exclusion criteria for concussion and control subjects included: 1) lower extremity deficiency or injury which may affect normal gait patterns, 2) history of cognitive deficiencies, such as permanent memory loss or concentration abnormalities, 3) history of three or more previous concussions, 4) loss of consciousness from the concussion lasting more than one minute, 5) history of attention deficit hyperactivity disorder, or 6) a previously documented concussion within the past year. A verbal history was taken for all subjects upon their first visit to the laboratory to confirm all criteria were met for inclusion in the study.

#### *Testing Timeline*

A prospective, repeated measures design was employed in which each subject reported to the laboratory and was tested within 72 hours of sustaining a concussion as well as on four subsequent testing days at the following time increments: one week, two weeks, one month, and two months post injury. Control subjects were similarly tested according to the same time schedule.

### *Protocol*

Subjects walked barefoot at a self-selected speed along a walkway under two conditions: walking with undivided attention (single-task) and walking while concurrently completing a continuous auditory Stroop test (dual-task). The Stroop test consisted of the subject listening to four auditory stimuli: the recorded words “high” or “low” each spoken in either a high pitch or low pitch. Subjects were instructed to correctly identify the pitch of the word, regardless of whether the pitch was congruent with the meaning of the word. The subjects were not instructed to focus attention specifically on the walking or cognitive task, but to continue walking while correctly responding to each pitch, and therefore neither the walking task nor Stroop test were prioritized. Each of the four stimuli was presented in random order at a specific time while walking. The first stimulus was presented once subjects had achieved steady state gait, and was triggered by a photocell located several steps after gait initiation. Each of the three subsequent stimuli was presented 1 second after the previous response while the subject continued to walk. Eight to ten consecutive trials were completed for each of the two conditions (single-task and dual-task).

A set of 29 retro-reflective markers were placed on bony landmarks of the subject (69) and whole body motion analysis was performed using a ten-camera motion analysis system (Motion Analysis Corp., Santa Rosa, CA) at a sampling rate of 60 Hz to capture and reconstruct the three-dimensional trajectory of each marker. Marker trajectory data were low-pass filtered using a fourth-order Butterworth filter with a cutoff frequency set at 8 Hz. External markers and estimated joint centers were used to calculate the center of mass (COM) position for each individual body segment. Whole body COM position data

were then calculated as the weighted sum of all body segments, using data from Winter (162) with 13 segments representing the whole body (head-neck, trunk, pelvis, upper arms, forearms and hands, thighs, shanks, and feet). Gait events were detected from ground reaction forces collected at 960 Hz using three force plates (Advanced Mechanical Technologies, Inc., Watertown, MA). Each Stroop test stimulus was presented in random order using Super Lab Pro (Cedrus Corp., San Pedro, CA). Participants verbally responded to the Stroop test using a headset wireless system with microphone (AKG Acoustics, Northridge, CA). For each trial, data were analyzed for one gait cycle, defined as heel strike to heel strike of the same limb. The targeted stride for analysis was after initial Stroop stimulus presentation and typically occurred during the first or second stimulus.

#### *Data Analysis*

Accuracy on each Stroop test response was calculated as the total correct responses divided by the total trials completed during each testing session for each subject. For gait temporal-distance variables, average walking speed was calculated as the mean forward velocity throughout the gait cycle. Step length and width were calculated as the distances between right and left heel markers at each heel strike in the anterior/posterior and medial/lateral directions, respectively. Linear COM velocity was calculated using the cross validated spline algorithm from COM position (163). The peak anterior and medial/lateral (M/L) COM velocities were identified during the gait cycle. The total M/L COM displacement during the gait cycle was also obtained. These variables were reported previously to provide sensitive detection of gait imbalance (70). In order to account for individual differences in attentional loading and walking speed



(168), the relative change between the single and the dual-task condition for each subject was calculated and reported as the percent change from the single to the dual-task condition (dual-task cost). The mean of each block of trials for all variables was computed for further analysis.

### *Statistical Analysis*

Group demographic differences were tested using an independent *t*-test for height, mass, and age. Three-way mixed effects analyses of variance were used to analyze each walking dependent variable in order to determine the effect of group (concussion and control), time (72 hours, one week, two weeks, one month, and two months), task (single and dual) and the interactions between these three independent variables. The dual-task cost dependent variables were calculated as the percentage change between the single and dual-task conditions and analyzed using a two-way mixed effects analysis of variance to examine the effect of group and time. Stroop test accuracy was also analyzed using a two-way mixed effect analysis of variance.

For all omnibus tests, significance was set at  $p < .05$ . Follow up pairwise comparisons were then examined using the Bonferroni procedure to control Family Wise Type I Error. All statistical analyses were performed with SPSS version 20.

## Results

### *Participants*

Subjects with concussion were tested in the following time increments: 2 ( $\pm 0.75$ ) days, 8 ( $\pm 1.8$ ) days, 17 ( $\pm 3.6$ ) days, 30 ( $\pm 2.6$ ) days, and 59 ( $\pm 3.5$ ) days following the injury. Control subjects followed a similar timeline and were tested at 8 ( $\pm 2.1$ ) days, 17

( $\pm 4.7$ ) days, 31 ( $\pm 3.7$ ) days, and 57 ( $\pm 6.4$ ) days after their initial testing session. No significant differences were observed between the concussion and control group (Table 2) for height ( $p = .812$ ), mass ( $p = .395$ ), or age ( $p = .558$ ). Both groups contained 18 males and 2 females. In one case, a direct sport match was not obtained (Table 2). Three of the concussion subjects had a previous history of concussion with the most recent concussion occurring greater than one year prior to beginning the study, while no control subject had a history of concussion.

**Table 2:** Demographic information for both groups of subjects (group mean  $\pm$  SD).

<b>Group</b>	<b>Sex (M/F)</b>	<b>Age (years)</b>	<b>Age (range)</b>	<b>Height (cm)</b>	<b>Weight (kg)</b>	<b>Sport Played (n)</b>
Concussion	18/2	15.3 $\pm$ 1.3	14-18	173.7 $\pm$ 6.4	74.8 $\pm$ 16.6	Football: 15 Soccer: 3 Volleyball: 1 Wrestling: 1 Basketball: 0
Control	18/2	15.6 $\pm$ 1.0	14-17	173.4 $\pm$ 8.1	70.7 $\pm$ 13.6	Football: 15 Soccer: 2 Volleyball: 1 Wrestling: 1 Basketball: 1

Concussion subjects presented at the 72 hour assessment with a mean symptom score of 40.7 ( $\pm 23.1$ , range = 10 to 99) while control subjects presented initially with a mean symptom score of 4.3 ( $\pm 4.1$ , range = 0 to 12). Clinical symptom resolution for concussion subjects, defined by a symptom score within two standard deviations of the control subject mean at the two month follow-up evaluation ( $4.8 \pm 6.7$ ), occurred for all but four concussion subjects.

### *Gait Temporal-Distance Parameters*

For average walking speed, both groups walked slower in the dual-task than in the single-task condition [group x task interaction,  $F(1, 37) = 5.53, p = .024, \eta_p^2 = .130$ ; time x task interaction,  $F(4,148) = 6.29, p = .001, \eta_p^2 = .145$ ; Table 3], however, the dual-task cost was significantly greater for the concussion group subjects with the control group across the two month testing period [main effect of group,  $F(1, 37) = 6.02, p = .019, \eta_p^2 = .140$ ; and time,  $F(4, 148) = 6.08, p = .001, \eta_p^2 = .141$ ; Table 4].

**Table 3:** Mean ( $\pm$  SD) temporal distance measures for concussion and control groups in single-task and dual-task walking conditions.

<u>Variable</u>	<u>Group</u>	<u>Task</u>	<u>72 hour</u>	<u>1 week</u>	<u>2 week</u>	<u>1 month</u>	<u>2 month</u>
Average Walking Speed (m/s)	Concussion	Single	1.16 ( $\pm$ 0.19)	1.22 ( $\pm$ 0.16)	1.25 ( $\pm$ 0.15)	1.26 ( $\pm$ 0.17)	1.32 ( $\pm$ 0.14)
		Dual*	1.06 ( $\pm$ 0.14)	1.14 ( $\pm$ 0.17)	1.16 ( $\pm$ 0.14)	1.18 ( $\pm$ 0.16)	1.20 ( $\pm$ 0.16)
	Control	Single	1.23 ( $\pm$ 0.11)	1.24 ( $\pm$ 0.14)	1.25 ( $\pm$ 0.14)	1.26 ( $\pm$ 0.14)	1.29 ( $\pm$ 0.14)
		Dual*	1.15 ( $\pm$ 0.13)	1.20 ( $\pm$ 0.12)	1.21 ( $\pm$ 0.13)	1.22 ( $\pm$ 0.13)	1.20 ( $\pm$ 0.12)
Step Length (m)	Concussion	Single	0.64 ( $\pm$ 0.06)	0.65 ( $\pm$ 0.05)	0.67 ( $\pm$ 0.06) †,‡	0.68 ( $\pm$ 0.06) †,‡	0.69 ( $\pm$ 0.06) †,‡
		Dual	0.61 ( $\pm$ 0.05)	0.63 ( $\pm$ 0.06)	0.65 ( $\pm$ 0.05) †,‡	0.66 ( $\pm$ 0.07) †,‡	0.66 ( $\pm$ 0.06) †,‡
	Control	Single	0.67 ( $\pm$ 0.04)	0.66 ( $\pm$ 0.05)	0.67 ( $\pm$ 0.05)	0.68 ( $\pm$ 0.05)	0.68 ( $\pm$ 0.05)
		Dual	0.64 ( $\pm$ 0.05)	0.66 ( $\pm$ 0.04)	0.66 ( $\pm$ 0.05)	0.67 ( $\pm$ 0.04)	0.66 ( $\pm$ 0.05)
Step Width (m)	Concussion	Single	0.09 ( $\pm$ 0.03)	0.09 ( $\pm$ 0.03)	0.09 ( $\pm$ 0.02)	0.09 ( $\pm$ 0.02)	0.09 ( $\pm$ 0.02)
		Dual	0.10 ( $\pm$ 0.02)	0.09 ( $\pm$ 0.02)	0.09 ( $\pm$ 0.03)	0.09 ( $\pm$ 0.03)	0.10 ( $\pm$ 0.03)
	Control	Single	0.09 ( $\pm$ 0.03)	0.08 ( $\pm$ 0.03)	0.09 ( $\pm$ 0.03)	0.09 ( $\pm$ 0.03)	0.09 ( $\pm$ 0.03)
		Dual	0.08 ( $\pm$ 0.03)	0.09 ( $\pm$ 0.04)	0.09 ( $\pm$ 0.03)	0.09 ( $\pm$ 0.03)	0.09 ( $\pm$ 0.03)

\* = significantly slower than single-task condition

† = significantly greater than 72 hour assessment

‡ = significantly greater than one week assessment

No between-group or between-task differences were observed for step length and step width. However, the concussion group step length significantly increased after two weeks post injury compared to the 72 hour and 1-week testing sessions for single and dual-task conditions [group x time interaction,  $F(4, 148) = 3.82, p = .012, \eta_p^2 = .094$ ; Table 3]. Step length dual-task cost analysis demonstrated no interaction ( $p = .762$ ), main effect of time ( $p = .102$ ) or group ( $p = .096$ ; Table 3). Step width analysis revealed no significant interactions or main effects of group ( $p = .737$ ), time ( $p = .064$ ), or task ( $p = .860$ ). Similarly, step width dual-task cost analysis revealed no main effects of group ( $p = .811$ ) or time ( $p = .352$ ), or interaction between the two ( $p = .520$ ; Table 4).

#### *Peak Anterior COM Velocity*

Concussion subjects demonstrated a significant increase in peak anterior COM velocity from the initial time tested until the two month post-injury assessment while control subjects showed no significant differences across time [group x time interaction,  $F(4, 148) = 3.23, p = .037, \eta_p^2 = .080$ ; Figure 5A]. Both groups demonstrated significantly higher peak anterior COM velocity in the single-task condition than in the dual-task condition [group x task interaction,  $F(1, 37) = 5.99, p = .019, \eta_p^2 = .139$ ; Figure 5A]. During single-task walking, both groups exhibited a significantly higher peak anterior velocity at two months than on any other previous testing session, while in the dual-task condition, both groups walked with a significantly lower peak COM anterior velocity at the 72 hour testing session than any other subsequent testing time [time x task interaction,  $F(4, 148) = 6.67, p = .001, \eta_p^2 = .153$ ; Figure 5A]. The Stroop test perturbation induced a significantly greater peak COM anterior velocity reduction for concussion subjects compared to control subjects [dual-task cost; main effect of group,

$F(1, 37) = 6.23, p = .017, \eta_p^2 = .144$  and time,  $F_{4,148} = 6.46, p = .001, \eta_p^2 = .149$ ; Table 4].

#### *Peak Medial/Lateral COM Velocity and Displacement*

No significant three-way or two-way interactions were found for the peak medial/lateral COM velocity. However, concussion subjects demonstrated significantly higher peak M/L COM velocity than control subjects [main effect of group,  $F(1, 37) = 5.32, p = .027, \eta_p^2 = .126$ ; Figure 5B]. Both groups walked with a significantly greater peak M/L COM velocity during the dual-task condition compared with the single-task condition [main effect of task,  $F(1, 37) = 7.42, p = .010, \eta_p^2 = .167$ ; Figure 5B]. The dual-task cost analysis for peak M/L COM velocity (Table 4) demonstrated no interaction ( $p = .701$ ), main effect of time ( $p = .355$ ) or group ( $p = .583$ ).

The concussion group walked with significantly greater total M/L COM displacement in the dual-task condition compared to the single-task condition and compared to the dual-task condition of the control group [group x task interaction,  $F(1, 37) = 8.65, p = .006, \eta_p^2 = .189$ ; Figure 5C]. The total M/L COM displacement dual-task cost was significantly greater for concussion subjects compared to controls across the two months of testing [dual-task cost; main effect of group,  $F(1, 37) = 6.75, p = .013, \eta_p^2 = .154$ ; Table 4].

#### *Stroop Test Accuracy*

The accuracy of control subjects on the Stroop test was significantly greater than subjects with concussion throughout the two month testing period [main effect of group,  $F(1, 37) = 9.45, p = .004, \eta_p^2 = .203$ ; Table 5].

**Table 4:** Values (Mean  $\pm$  SD) are expressed as the mean percent change between single and dual-task conditions (dual-single/single) for both groups across the two month testing period. A positive value indicates an increase from the single-task to dual-task condition while a negative value indicates a decrease.

<u>Variable</u>	<u>Group</u>	<u>72 hour</u>	<u>1 week</u>	<u>2 week</u>	<u>1 month</u>	<u>2 month</u>
Anterior Velocity <sup>*,†</sup>	Concussion	-8.23% ( $\pm 7.5$ )	-5.66% ( $\pm 7.0$ )	-7.17% ( $\pm 6.1$ )	-6.05% ( $\pm 4.6$ )	-9.08% ( $\pm 6.5$ )
	Control	-7.11% ( $\pm 8.0$ )	-1.93% ( $\pm 4.2$ )	-2.38% ( $\pm 3.2$ )	-2.54% ( $\pm 3.2$ )	-6.42% ( $\pm 4.3$ )
M/L Velocity	Concussion	8.85% ( $\pm 22.4$ )	2.99% ( $\pm 20.1$ )	11.77% ( $\pm 30.0$ )	7.61% ( $\pm 27.5$ )	8.32% ( $\pm 18.4$ )
	Control	3.64% ( $\pm 33.6$ )	4.84% ( $\pm 20.2$ )	14.40% ( $\pm 29.8$ )	7.64% ( $\pm 24.4$ )	-0.29% ( $\pm 23.3$ )
M/L Displacement <sup>*</sup>	Concussion	13.92% ( $\pm 35.1$ )	18.17% ( $\pm 28.2$ )	14.34% ( $\pm 17.5$ )	10.35% ( $\pm 29.0$ )	12.39% ( $\pm 26.2$ )
	Control	3.68% ( $\pm 21.4$ )	2.06% ( $\pm 26.1$ )	14.15% ( $\pm 40.3$ )	6.62% ( $\pm 27.6$ )	-1.57% ( $\pm 17.9$ )
Avg Walk Speed <sup>*,†</sup>	Concussion	-8.65% ( $\pm 8.0$ )	-6.22% ( $\pm 7.0$ )	-7.33% ( $\pm 5.7$ )	-6.45% ( $\pm 4.7$ )	-9.12% ( $\pm 7.0$ )
	Control	-6.74% ( $\pm 7.7$ )	-2.44% ( $\pm 4.3$ )	-2.59% ( $\pm 3.4$ )	-2.68% ( $\pm 3.1$ )	-6.98% ( $\pm 4.6$ )
Step Length	Concussion	-4.46% ( $\pm 7.2$ )	-3.94% ( $\pm 4.9$ )	-3.73% ( $\pm 6.3$ )	-2.45% ( $\pm 5.6$ )	-4.76% ( $\pm 4.9$ )
	Control	-3.29% ( $\pm 5.9$ )	-0.76% ( $\pm 3.9$ )	-1.73% ( $\pm 3.0$ )	-1.39% ( $\pm 1.86$ )	-3.65% ( $\pm 2.7$ )
Step Width	Concussion	4.16% ( $\pm 20.8$ )	1.73% ( $\pm 22.4$ )	-2.49% ( $\pm 17.5$ )	-0.93% ( $\pm 26.3$ )	0.60% ( $\pm 17.8$ )
	Control	-1.89% ( $\pm 18.3$ )	7.30% ( $\pm 15.6$ )	-0.96% ( $\pm 11.3$ )	1.76% ( $\pm 16.2$ )	-0.65% ( $\pm 18.3$ )

*Note:* All values are expressed as a percent change from single to dual-task walking conditions.

\* = main effect of group

† = main effect of time

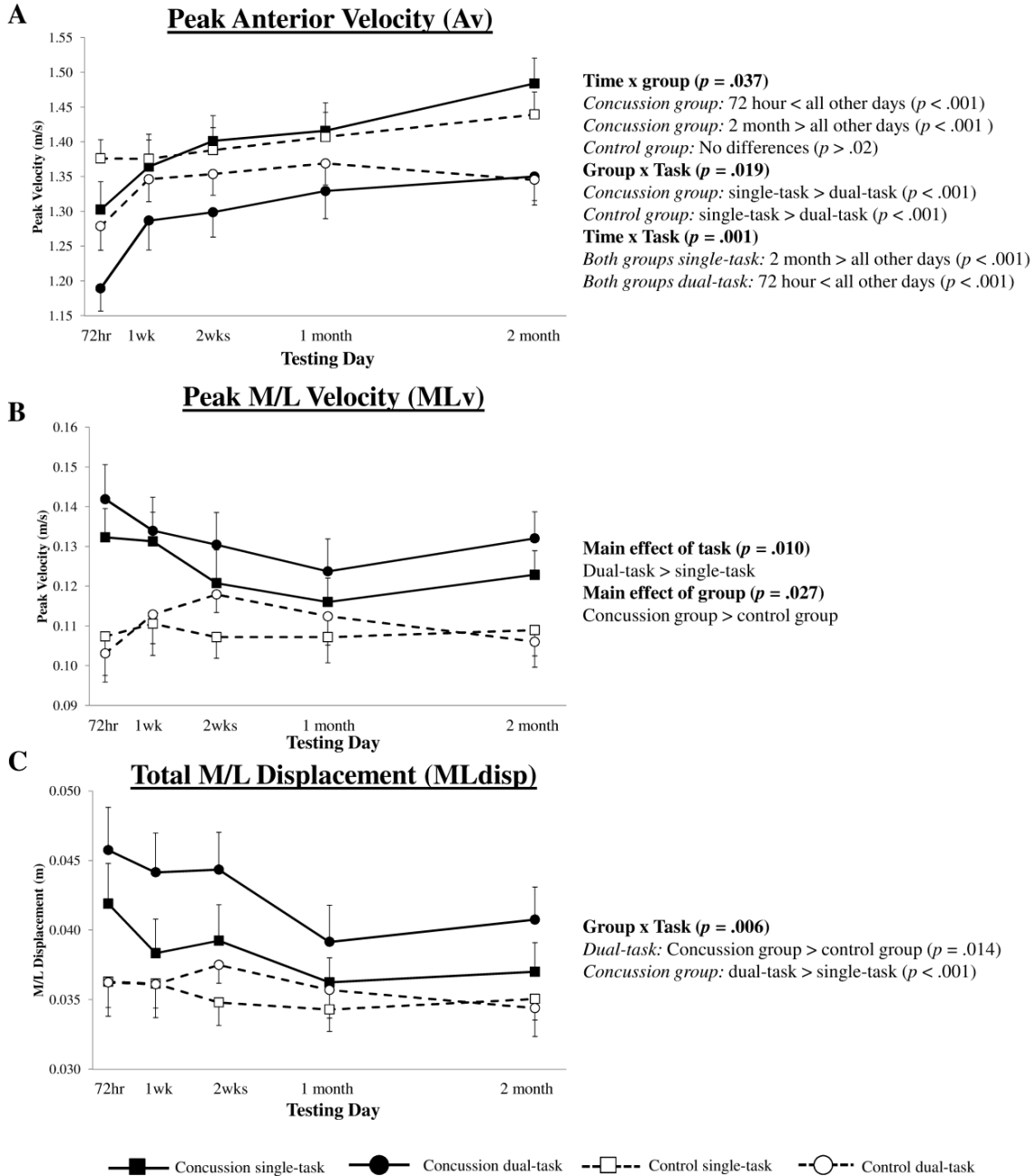
**Table 5:** Stroop test accuracy rates during walking for concussion and control subjects.

<u>Testing Day</u>	<u>Concussion*</u>	<u>Control</u>
72 hour	96.6% ( $\pm 5.0$ )	99.4% ( $\pm 1.3$ )
1 week	96.8% ( $\pm 4.6$ )	98.9% ( $\pm 2.2$ )
2 week	97.6% ( $\pm 4.8$ )	99.6% ( $\pm 1.1$ )
1 month	97.7% ( $\pm 3.9$ )	99.6% ( $\pm 1.0$ )
2 month	97.5% ( $\pm 3.2$ )	99.4% ( $\pm 1.5$ )

\* = Main effect of group,  $p = .004$

### Discussion

The results of this study indicate adolescents with concussion are disrupted in their ability to control forward momentum and maintain gait balance control to a greater degree than control subjects while walking and performing a concurrent cognitive task. Subjects with concussion demonstrated a greater dual-task cost on peak COM anterior velocity and total COM M/L displacement variables throughout the two month testing period compared with control subjects. Subjects with concussion also displayed a higher COM M/L velocity and displacement within the dual-task condition compared with control subjects across the two months of testing, while step length resolved within two weeks of the injury and step width was not significantly affected by testing period.



**Figure 5:** Results across the two month testing period for COM variables: (A) peak anterior COM velocity, (B) peak M/L COM velocity, and (C) total M/L COM displacement. Statistically significant results from a three-way ANOVA with pairwise follow-up comparisons are listed to the right of each figure.

Previous literature has reported subjects with moderate to severe traumatic brain injury adopt shorter stride lengths post-injury compared with a cohort of healthy controls



(159). The current data revealed the step length of concussion subjects significantly increased one week after the injury while no change was observed across time in the control group. Although no significant between-group differences were observed for step length, the values of the concussion group more closely approximated the controls after one week post-injury.

Temporal distance and COM parameters have been used as measurements central to understanding balance control (102, 129). Previous work has demonstrated the utility of COM analysis in detecting disturbances in individuals suffering from concussion (127) and suggests deficits in COM control may indicate a disrupted ability to maintain gait stability (28). The current data are in agreement with those findings in that total medial/lateral COM displacement and peak COM medial/lateral velocity were significantly higher in the concussion group compared to the control group during dual-task walking for two months following injury.

The greater peak anterior COM velocity dual-task cost for subjects with concussion noted in the current study may be the result of an adaption previously reported to reflect a mobility impairment, and may be due in part to an effort to reduce COM forward momentum in order to accommodate to divided attention (28). This may indicate a disruption in motor or cognitive function during walking, or a disruption of the integration between these two functions. This is consistent with other literature, which suggests that attentional resources are limited in young adults suffering from concussion (30).

In the current study, the accuracy of control subjects on the Stroop test was significantly greater than subjects with concussion throughout the two month testing

period. These data suggest that in adolescents, concussion not only affects gait performance, but appears to affect response accuracy during walking. As all subjects were not instructed to focus their attention on either task, it is possible that the adolescents with concussion were not able to properly allocate their attentional resources to the same degree as healthy adolescents. Those suffering from concussion have been reported to have difficulty properly allocating attentional resources while performing one or more tasks simultaneously (31, 32, 34). Furthermore, it has been previously observed that the reaction time cost of switching from one task to another is significantly greater in adolescents with concussion when compared to control subjects throughout a two-month testing period following injury (76). Hence, as the frontal regions of the brain are believed to play a role in focus of attention (153) and among the last to develop (150), this region of the adolescent brain may be more susceptible to the effects of concussion and deficits may last longer than older age groups (4). The accuracy difference between groups along with the anterior COM velocity dual-task cost and increased total M/L displacement group differences indicates both cognitive and motor domains are affected for up to two months following concussion. These data also suggest that challenging cognitive and motor systems simultaneously following concussion may provide insights into how an affected individual may respond to mental and physical activities common in daily living, which require complex cognitive and motor interactions.

Greater M/L COM displacement and velocity were observed in the dual-task condition for concussion subjects compared with control subjects for a period of two months following injury. These differences may reflect a balance control deficiency in the concussion subjects rather than intentional gait disruption to accommodate to

incoming cognitive stimuli. Previous reports have linked increased frontal plane COM sway and velocity with balance impairments in young adults suffering from concussion (127), suggesting that a tradeoff between forward and side-to-side movement is brought on by a necessary reduction in COM forward velocity, and may reflect an inability to control balance. This impairment is consistent with literature which has described balance deficits in those suffering from a single concussion in young adult populations (103, 127).

The Stroop test, when performed in conjunction with another task such as walking, has been shown to activate the prefrontal cortex (PFC) which has been postulated to be crucial for the coordination of mental operations (62) and has been reported to be affected by concussion for up to one month after injury (71). The PFC also contributes to goal-directed action by configuring, modulating, and processing information to complete goal-related task demands (140). The current study findings are consistent with others as the simultaneous execution of a secondary task during walking resulted in decreased forward gait velocity (151) and this reduction was significantly greater in the concussion group than the control group. During physical activities of daily living, an individual must move and think simultaneously to perform the intended task efficiently and safely. If the ability to walk is inordinately affected by the implementation of a single additional task, individuals suffering from concussion may be less able to avoid hazards during normal activities and thus susceptible to further injury for a prolonged period of time during the post-concussion period (5).

### *Study Limitations*

Concussion severity was likely not uniform across all subjects as it has been documented that concussion severity is quite variable (49). This variability possibly results from differences in injury history and mechanism of injury. As it would be extremely difficult to prospectively constitute a concussion group of homogenous severity, strict inclusion criteria were incorporated in this study to mitigate this limitation. Additionally, some subjects were cleared to return to unrestricted physical activity within one week of injury while others did not return within the two months of testing. It is possible variability in treatment could have affected the results; however no subject was diagnosed with a second concussion while completing the course of the current study.

### Conclusion

Concussion reduces balance control ability during dual-task walking up to two months following injury in adolescents. The results of the study suggest examination of dynamic balance control during dual-task walking may provide additional useful information in the clinical assessment and recovery from concussion.

### Bridge

Chapter III identified, for the first time in a group of adolescents with concussion, that balance control abilities during dual-task walking may be affected for a time period of up to two months post-injury. Results also indicated that performance on the cognitive tasks was decreased in the concussion group. However, these results were found using two different conditions, walking and walking while completing a multiple auditory

Stroop task. Thus, the way cognitive tasks of varying complexity affect gait balance control post-concussion remain unknown and require further investigation. The comparison of cognitive task complexity within a dual-task investigation will allow researchers and clinicians to better understand the role of varying cognitive tasks implemented while walking, and how completion of varying cognitive tasks may affect motor function following injury.

## CHAPTER IV

### STUDY 3: THE EFFECT OF COGNITIVE TASK COMPLEXITY ON GAIT STABILITY IN ADOLESCENTS FOLLOWING CONCUSSION

This work was accepted for publication in the journal *Experimental Brain Research* in February, 2014. David Howell contributed to the concept of the study, recruited subjects, coordinated and supervised data collection, wrote analysis software, performed initial data analysis and statistical analysis, and prepared the initial manuscript. Michael Koester contributed to the concept of the study and recruitment of potential subjects. Louis Osternig and Li-Shan Chou contributed to the concept of the study, the analysis and interpretation of the data, and critically reviewed and revised the manuscript.

#### Introduction

The management of concussion, particularly related to concussion in sport, has recently become a dynamically evolving area of interest to researchers and clinicians alike. As a result of the complexity of this injury, different medical and sport agencies have recently released evidence-based position statements regarding the scope, pathophysiology, diagnosis, and follow up care of concussion (61, 73, 112). Although isolated cognitive evaluations have been traditionally thought to be a key element in concussion management (63), it has been suggested that such assessments should never be the sole basis of concussion management, but rather as aids in the clinical evaluation (112). Balance and gait testing have been increasingly identified as available tools

documented to aid in the identification of how individuals recover from concussion (73) and as integral components of a comprehensive evaluation (112). Thus, an evaluation which simultaneously assesses cognitive and motor functions may constitute an effective assessment technique for the monitoring of recovery from concussion.

Many investigations have simultaneously assessed motor and cognitive functions following brain injury through the use of a dual-task paradigm (50, 77, 115, 129). These types of evaluations can measure motor function while performing a cognitive task or vice versa. Using dual-task experiments, investigators have identified deficits in individuals who sustained a concussion for a time of approximately one month (50, 128) to many years (103) following injury.

While concussion has been observed to be a multi-dimensional injury which affects body movement control and cognitive processes when executed simultaneously (148), no investigations to this point have examined how secondary tasks of varying complexity affect the motor performance of individuals acutely suffering from concussion. Adolescents, in particular, may be particularly vulnerable to the effects of concussion due to the development of frontal structures of the brain during this time of life (97). Previous experiments have identified deficits still present at two months after concussion in a cohort of adolescents in their conflict resolution, task switching, and dual-task gait balance control abilities (76, 77).

Dual-task assessments necessitate proper distribution of attentional resources, thus challenging the brain to effectively execute both tasks simultaneously (168). This type of testing represents a way to observe performance differences of a motor task with and without the simultaneous performance of cognitive tasks. Two common cognitive

tests that have been reported as effective secondary tasks when introduced simultaneously during motor performance have been a question and answer task, such as continuous subtraction (29) and the Stroop task, which has recently been reported to be an appropriate tool in the follow up care of concussion (156) and commonly used when monitoring the effects of sport-related concussion (50, 156, 159). Experiments using functional magnetic resonance imaging (fMRI) indicated that the Stroop test activates a focal region of frontal lobe structures, such as the dorsal anterior cingulate gyrus (24) or the prefrontal cortex (PFC) (51).

Question and answer tasks, such as reciting the months in reverse order, have been utilized in the sideline care of sport concussion via standardized concussion assessment tools (111). fMRI investigations have revealed that arithmetic tasks engage a high number of cognitive processes as well as activation in the parietal areas of the brain, and other brain areas such as the fusiform and lingual gyri, Brodman's area, the prefrontal cortex, and thalamus (139). Spelling tasks have similarly been observed to activate a complex network of brain structures, including the left inferior frontal gyrus, left middle/superior frontal gyrus, left superior parietal lobe, and left fusiform gyrus (134). These investigations suggest that question and answer tasks require multiple brain area activation for successful completion.

Accordingly, a Stroop task which is performed only once during a testing session represents a less complex task than one performed multiple times in succession during a similar session. An increase in complexity between two such conditions is a result of the necessary increase of sustained attention for completion. A question and answer task represents a more complex condition than a multiple Stroop condition as it possesses



similar temporal demands as a continuous Strop task, but with an increased integrative requirement of multiple brain structures to coordinate and execute such a task.

Dual-task paradigms are commonly used in the recovery monitoring and management of concussion suggesting that protocols involving simultaneous attention to cognitive and dynamic/static postural stability may reveal subtle post-concussion disturbances better than single-task paradigms (138, 143). However, to our knowledge, no current literature exists which directly compares the effects of secondary tasks of differing complexity on gait performance. Therefore, the purpose of this study was to prospectively examine how gait balance control is affected by secondary cognitive tasks of varying complexity implemented simultaneously while walking in a population of adolescents with and without concussion. It was hypothesized that 1) secondary tasks of greater complexity would result in greater disturbances to walking balance control than less complex secondary tasks and single-task walking in subjects with concussion and 2) that concussion subjects would be affected by each secondary task to a greater degree than control subjects.

## Methods

### *Participants*

Twenty-three high school students (20 males/3 females) were identified as sustaining a concussion while participating in school sports by a health professional (certified athletic trainer or physician). The definition of concussion was consistent with that of the 3<sup>rd</sup> International Consensus Statement on Concussion in Sport as an injury caused by a direct blow to the head, face, neck, or elsewhere in the body with an

impulsive force transmitted to the head, resulting in impaired neurologic function and acute clinical symptoms (111). Each subject reported to the laboratory for testing within 72 hours of injury, and returned approximately one week, two weeks, one month, and two months post-injury. Each subject who sustained a concussion was then matched with a healthy control subject by sex, height, mass, age, and sport and tested in a similar timeline. Prior to data collection, the institutional review board reviewed and approved the protocol of the current study. All subjects and parent/guardian (if under the age of 18) provided informed consent. Permission was also granted by each respective school district to conduct testing with student participants.

Each subject who suffered a concussion was removed from physical activity on the day of injury and did not return until cleared by a physician in accordance with state law. Exclusion criteria for all subjects included: 1) lower extremity deficiency or injury which may affect normal gait patterns, 2) history of cognitive deficiencies, such as permanent memory loss or concentration abnormalities, 3) history of three or more previous concussions, 4) loss of consciousness from the concussion lasting more than one minute, 5) history of attention deficit hyperactivity disorder, or 6) a previously documented concussion within the past year. Consistent with previous work (76), individuals with three or more previous concussions were ineligible to participate in the study to ensure, to the extent possible, the exclusion of subjects experiencing chronic concussion and those who experienced a loss of consciousness for greater than one minute were excluded because of the role this sign plays in concussion management modification (111). A verbal medical history was taken by a certified athletic trainer for all subjects upon their first visit to the laboratory to confirm all criteria were met for

inclusion in the study. Additionally, a symptom inventory was administered to all subjects using a 22-symptom inventory adapted from the SCAT2 (111), which requires subjects to identify the severity of each documented symptom of concussion using a 6 point Likert scale. This inventory indicates the sum of all symptom severity ratings (range: 0 to 132).

### *Protocol*

The protocol for every subject included one single-task and three dual-task walking conditions. For the single-task condition (WALK), the subject walked with undivided attention while barefoot at a self-selected speed along a walkway. For each of the three dual-task conditions, the subject walked along the same walkway but while simultaneously responding to one of three presented cognitive tasks. The order of presentation for the three cognitive tests changed for each of the five testing sessions (72 hours, 1 week, 2 weeks, 1 month, and 2 months) but was consistent and completed in the same order for all subjects. The three cognitive tasks, in order of complexity, were: 1) a single auditory Stroop (SAS), 2) a multiple auditory Stroop (MAS), and 3) a question and answer task (Q&A). The SAS task required the subject to listen to the words “high” or “low” played one time per trial by computer speakers in a high or low pitch and then identify the pitch of the word, regardless of whether the pitch was congruent with the meaning. The MAS tasks was similar to the SAS, except the words “high” or “low” were played and the subjects were required to respond four times per trial. Each “high” or “low” stimulus after the first was triggered by the previous response of the subject and was presented one second following the subject response. The Q&A consisted of answering one question per walking trial: spelling a five-letter word backwards,

subtracting by 6s or 7s, or reciting the months in reverse order. The type of Q&A task completed was randomly selected for each trial to avoid learning effects from one trial to the next. The subjects completed 8-10 trials for each of the single and dual-task conditions.

During dual-task walking, subjects were not instructed to focus on either the cognitive or walking task, but to continue walking while correctly completing the task. For the SAS and MAS conditions, the stimuli were presented once subjects had reached steady-state gait, several steps after gait initiation, and were triggered by a photocell. The instructions for the Q&A task were given to the subjects prior to gait initiation after which they were instructed to begin walking and respond to the task once an auditory beep was played, triggered by a photocell located several steps after gait initiation. For each walking trial, data were analyzed for one gait cycle, defined as heel strike to heel strike of the same limb. The targeted stride for analysis was the one immediately after initial task-stimulus presentation.

A total of 29 retro-reflective markers were placed on bony landmarks of the subject and whole body movement was recorded using a ten camera motion analysis system (Motion Analysis Corp., Santa Rosa, CA) at a sampling rate of 60 Hz to capture and reconstruct the three-dimensional trajectory of each marker. Marker trajectory data were low-pass filtered using a fourth-order Butterworth filter with a cutoff frequency set at 8 Hz. External markers and estimated joint centers were used to calculate the center of mass (COM) of each individual body segment. Whole body COM position data were then calculated as the weighted sum of all body segments (162) with thirteen segments representing the whole body (head/neck, trunk, pelvis, two arms, two forearms/hands,

two thighs, two legs, and two feet). Gait events were detected from ground reaction forces collected at 960 Hz using three forceplates (Advanced Mechanical Technologies Inc., Watertown, MA). Both SAS and MAS stimulus was presented in random order using Super Lab Pro (Cedrus Corp., San Pedro, CA). Verbal responses to each task were recorded using a headset wireless system with a microphone (AKG Acoustics, Northridge, CA).

#### *Data Analysis*

Linear COM velocity was calculated using the cross-validated spline algorithm from COM position (163). The total medial/lateral COM displacement, peak anterior COM velocity and peak medial/lateral (M/L) COM velocity were calculated and identified during the gait cycle. Peak M/L and anterior COM velocities occurred during the heel strike event of the gait cycle. These variables have previously been used to provide sensitive detection of gait imbalance in elderly individuals (70) and in those suffering from concussion (128). Average walking speed was also calculated as the mean forward velocity during the gait cycle. The mean of the 8-10 trials for each subject was calculated for each variable.

Cognitive task accuracy was recorded by the experimenter during the testing session while subjects completed walking trials. Accuracy was analyzed for each of the three conditions as the total number of correct responses divided by the total number of responses completed during all walking trials.

#### *Statistical Analysis*

Group demographic differences and testing time differences were tested using an independent *t*- test for height, mass, age, and testing day. Three-way mixed effects

analyses of variance were used to analyze each dependent variable to determine the interactions and main effects of group (concussion and control), time (72 hours, one week, two weeks, one month, and two months), and task (WALK, SAS, MAS, Q&A). For all omnibus tests, significance was set at  $p < .05$ . Follow up pairwise comparisons were then examined using the Bonferroni procedure to control Family Wise Type I Error. All statistical analyses were performed with Statistical Package for the Social Sciences version 20 (SPSS Inc., Chicago, IL).

## Results

### *Subjects*

Demographic and injury data for the subjects groups are presented in Table 6. No significant differences were detected between groups for age ( $p = .494$ ), height ( $p = .793$ ), or mass ( $p = .549$ ). The concussion group included 15 football athletes, 4 soccer athletes, 3 wrestling athletes, and 1 volleyball athlete. The control group included 15 football athletes, 3 soccer athletes, 3 wrestling athletes, 1 volleyball athlete, and 1 basketball athlete.

**Table 6:** Demographic and injury history information for both groups of subjects.

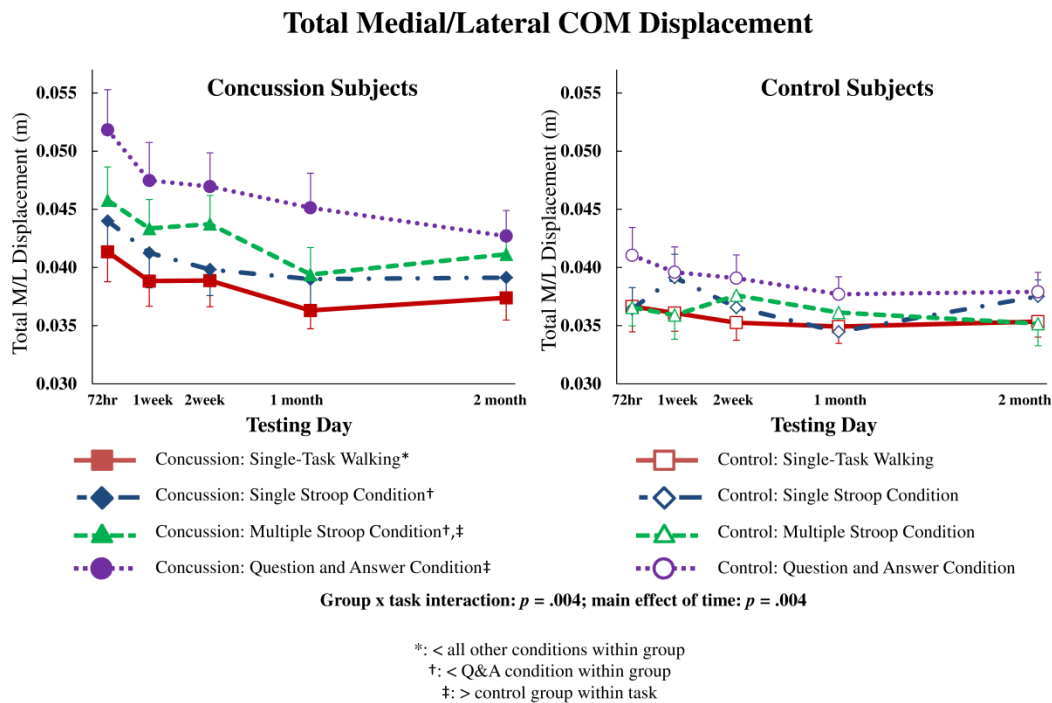
<b>Subject Characteristics</b>	<i>Concussion Subjects</i>	<i>Control Subjects</i>
Age (years)	$15.4 \pm 1.3$	$15.7 \pm 1.3$
Sex (M/F)	20/3	20/3
Height (cm)	$173.7 \pm 6.1$	$173.2 \pm 7.8$
Mass (kg)	$73.0 \pm 16.1$	$70.4 \pm 12.7$
Loss of consciousness lasting 30 seconds or less ( $n$ )	4	N/A
History of concussion greater than one year prior to initial testing day ( $n$ )	5	1

The concussion group was initially tested at a mean of  $2 \pm 0.7$  days after sustaining a concussion and returned for testing at means of  $8 \pm 1.7$ ,  $17 \pm 3.4$ ,  $31 \pm 4.1$ , and  $59 \pm 3.4$  days after injury. The control group was similarly tested at means of  $8 \pm 2.0$ ,  $16 \pm 4.5$ ,  $31 \pm 3.6$ , and  $57 \pm 6.0$  days after the initial testing session. No significant differences in testing times for each assessment were detected between the groups ( $p > .30$ ). Similar to previous work (76), evaluation of clinical symptom severity scores indicated a significant group x time interaction [ $F(4, 176) = 15.64, p < .001, \eta_p^2 = .262$ ]. Follow-up pairwise tests indicated a significant difference between the concussion and control groups (mean  $\pm$  SD) at the 72 hour time point ( $p < .001$ , concussion =  $41.6 \pm 24.1$ , control =  $4.5 \pm 4.8$ ), one week time point ( $p < .001$ , concussion =  $28.4 \pm 23.5$ , control =  $3.3 \pm 5.1$ ), and two week time point ( $p = .004$ , concussion =  $19.7 \pm 20.9$ , control =  $4.4 \pm 9.2$ ). Differences were no longer detected between groups at the one month ( $p = .060$ , concussion =  $11.8 \pm 13.6$ , control =  $4.2 \pm 6.9$ ) or two month testing time points ( $p = .308$ , concussion =  $8.7 \pm 17.4$ , control =  $4.4 \pm 6.3$ ).

#### *Total M/L COM Displacement*

Analysis of the total M/L COM displacement during the gait cycle (see Figure 6) revealed a significant group x task interaction [ $F(3, 129) = 5.31, p = .004, \eta_p^2 = .110$ ] and a main effect of time [ $F(4, 172) = 4.67, p = .004, \eta_p^2 = .098$ ]. Pairwise follow-up comparisons indicated that in the MAS and Q&A conditions, the concussion group displayed significantly more total M/L COM displacement than control subjects at each time point throughout the two months of testing, but not in the WALK or SAS conditions. Additionally, for the concussion group, there was significantly less total

medial/lateral COM displacement in the WALK condition than for any of the other three conditions and significantly more total medial/lateral COM displacement in the Q&A condition compared with the WALK, SAS, and MAS conditions. No significant differences were found between the four conditions for the control group. Pairwise follow-up comparisons for the main effect of time revealed significantly greater total medial/lateral COM displacement at the 72 hour assessment compared to the one month assessment in both subject groups.



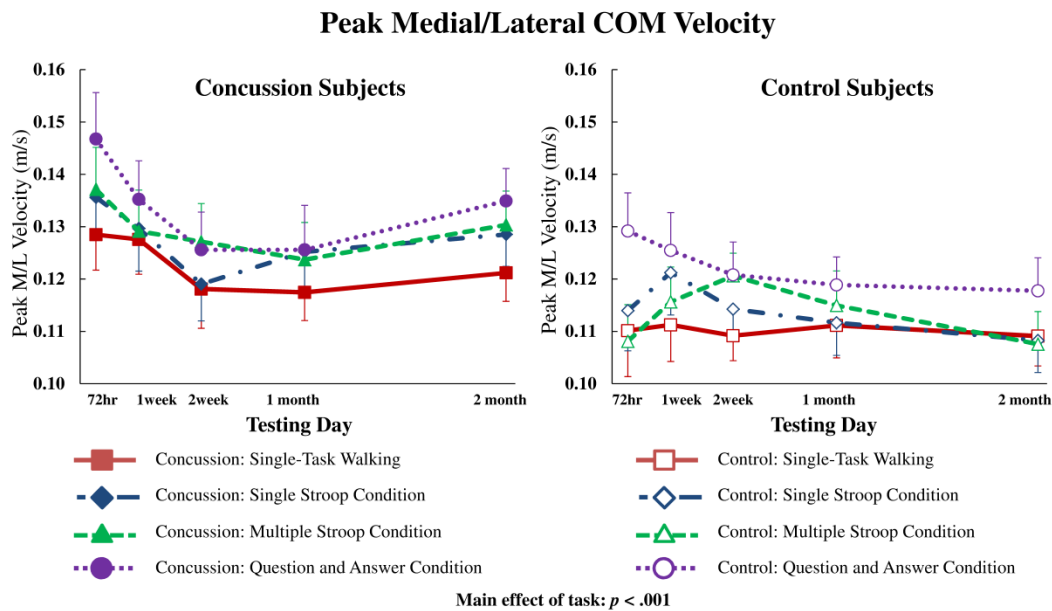
**Figure 6:** Mean  $\pm$  SE results across the two month testing period for total M/L displacement for both groups in each of the four walking conditions. Results indicated a significant group x task interaction and main effect of time.

### *Peak M/L COM Velocity*

Peak medial/lateral COM velocity analysis revealed no significant three-way or two-way interactions ( $p > .125$ ), but detected a main effect of task [see Figure 7:  $F(3,$



129) = 11.19,  $p < .001$ ,  $\eta_p^2 = .206$ ]. Follow-up pairwise comparisons indicated that both groups of subjects demonstrated significantly less peak M/L COM velocity in the WALK, SAS, and MAS conditions compared with the Q&A condition ( $p < .01$ ). Main effects of group [ $F(1,43) = 3.06$ ,  $p = .088$ ,  $\eta_p^2 = .066$ ] and time [ $F(4,172) = 2.41$ ,  $p = .052$ ,  $\eta_p^2 = .053$ ] were not statistically significant.



**Figure 7:** Mean  $\pm$  SE results across the two month testing period for peak M/L velocity for both groups in each of the four walking conditions. Results indicated a significant main effect of task with the Q&A condition displaying significantly greater peak M/L velocity than all other conditions.

### *Peak Anterior COM Velocity*

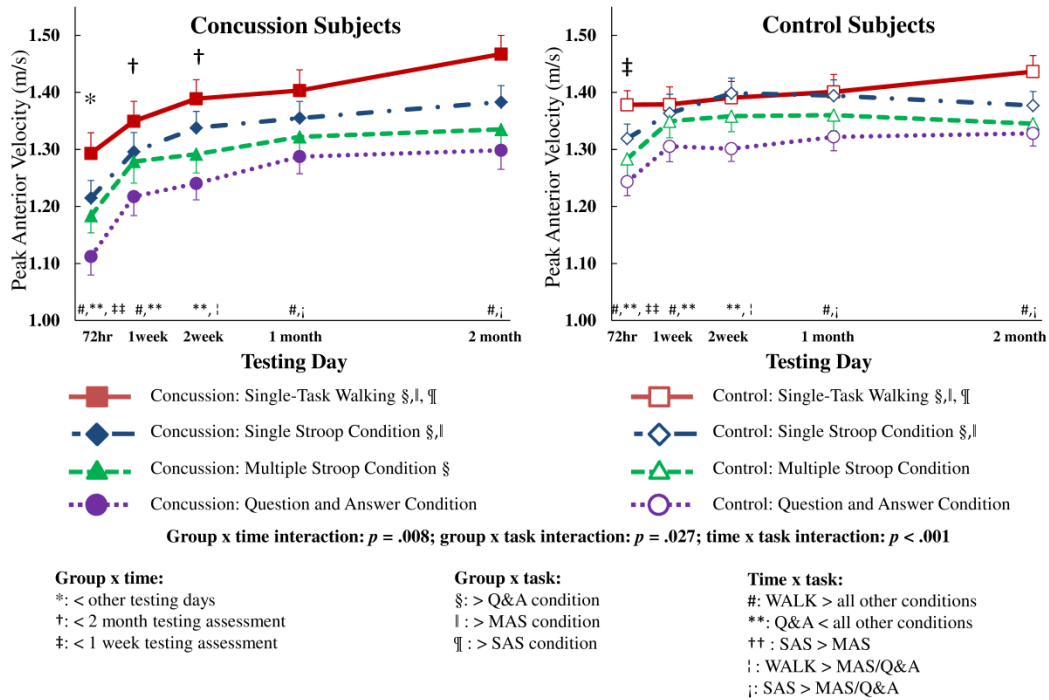
Three separate two-way interactions were detected for the peak anterior COM velocity (See Figure 8). For the group x time interaction [ $F(4, 172) = 4.44$ ,  $p = .008$ ,  $\eta_p^2 = .094$ ], results indicated that the concussion group walked with a smaller peak anterior COM velocity within 72 hours of injury compared with all subsequent testing times and a smaller peak anterior COM velocity at the one and two week assessment in comparison

to the two month assessment. Control subjects walked with less peak COM anterior velocity at the initial testing assessment compared with the one week testing assessment. The group x task interaction [ $F(3, 129) = 3.80, p = .027, \eta_p^2 = .081$ ], analysis indicated significant peak COM anterior velocity differences for concussion subjects between all four conditions (WALK>SAS>MAS>Q&A) while control subjects demonstrated significantly greater peak COM anterior velocity in the WALK compared with the SAS, MAS, or Q&A conditions, and significantly greater peak COM anterior velocity in the SAS than the MAS or Q&A conditions. The time x task interaction ( $F(12, 516) = 5.27, p < .001, \eta_p^2 = .109$ ) results indicated that in the WALK condition, all subjects displayed a smaller peak COM anterior velocity at the initial testing time compared with the two week, one month, and two month follow up and a larger peak COM anterior velocity at the two month visit compared with all other testing times. For the SAS, MAS, and Q&A conditions, all subjects walked with a significantly smaller peak COM anterior velocity at the first visit compared with all other time points. For the Q&A condition, the one week and two week follow-up visits were significantly less than the one month and two month visits.

#### *Average Walking Speed*

Three separate two-way interactions were detected for average walking speed (see Figure 9). The group x time interaction [ $F(4, 172) = 3.98, p = .015, \eta_p^2 = .085$ ] indicated that for the concussion group, the 72 hour post-injury visit was significantly slower than all other testing days, the one week visit was significantly slower than the two-month visit, and for the control group, the initial visit was significantly slower than the one week follow-up.

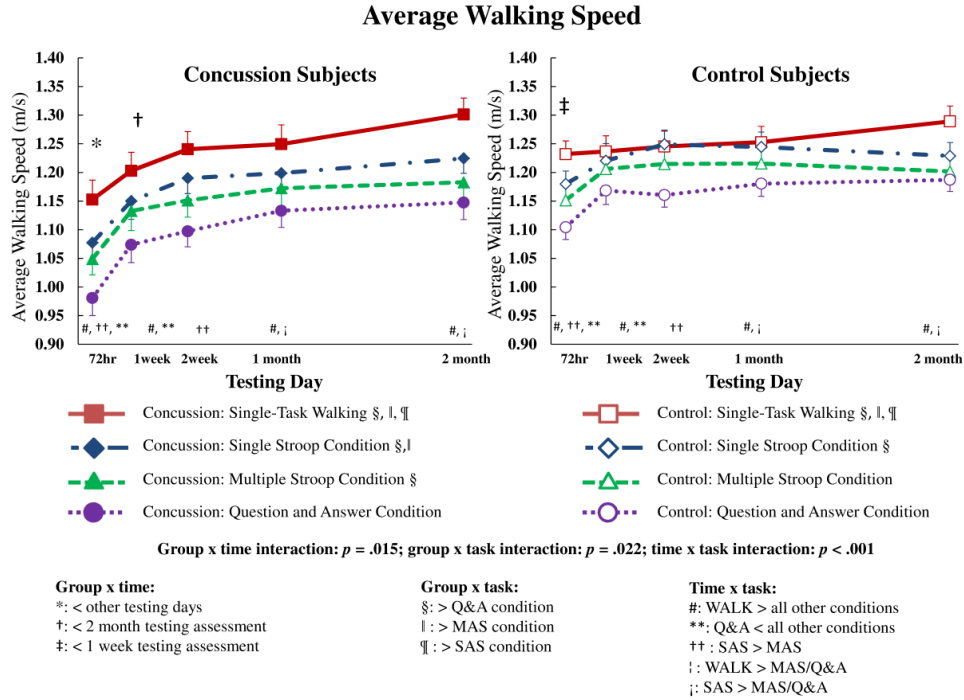
### Peak Anterior COM Velocity



**Figure 8:** Mean  $\pm$  SE results across the two month testing period for peak anterior velocity for both groups in each of the four walking conditions. Results indicated significant group x time, group x task, and time x task interactions.

For the group x task interaction [ $F(3, 129) = 4.11, p = .022, \eta_p^2 = .087$ ], no differences between groups on any task were detected, but the concussion group demonstrated significant differences between each condition (WALK > SAS > MAS > Q&A) while the control group walked with a faster average walking speed in the WALK condition compared with the other three conditions, and a greater walking speed in the SAS condition compared with the Q&A condition. The time x task interaction [ $F(12, 516) = 5.52, p < .001, \eta_p^2 = .114$ ] revealed the average walking speed for subjects in the WALK condition was less at the 72 hour visit in comparison to the one month visit, and

the two month visit was significantly faster than all other visits. For the SAS, MAS, and Q&A conditions, the 72 hour visit was significantly slower than all other visits.



**Figure 9:** Mean  $\pm$  SE results across the two month testing period for average walking speed for both groups in each of the four walking conditions. Results indicated significant group x time, group x task, and time x task interactions.

### Secondary Task Accuracy

Analysis of the secondary cognitive task accuracy revealed a three way (group x time x task) interaction [see Table 7;  $F(8, 344) = 2.728, p = .015, \eta_p^2 = .006$ ]. Follow up comparisons indicated that concussion subjects were significantly less accurate than control subjects on the MAS task at the 72 hour, one month, and two month testing time points and significantly less accurate on the SAS task at the one month testing time point. Concussion subjects were also more accurate on the SAS task at the two month testing assessment compared with the 72 hour and one month time points, and less accurate at the 72 hour time point than the two week time point.

**Table 7:** Cognitive test accuracy rates.

Task	Group	72 hour	1 week	2 week	1 month	2 month
Single Auditory Stroop	Concussion	92.6% (±10.5) †‡	97.7% (± 5.6)	98.7% (± 3.5)	97.3% (± 5.7)* †	99.5% (± 2.6)
	Control	96.9% (± 8.5)	97.1% (± 8.7)	99.6% (± 2.1)	100.0% (± 0.0)	100.0% (± 0.0)
Multiple Auditory Stroop	Concussion	96.2% (± 4.7)*	96.9% (± 4.3)	97.9% (± 4.5)	98.0% (± 3.8)*	97.6% (±3.0)* ¶
	Control	99.2% (± 1.7)	98.7% (± 2.3)	99.7% (± 1.0)	99.7% (± 1.0)	99.3% (± 1.5)
Question and Answer	Concussion	80.8% (± 13.2) †§	82.6% (± 14.6) †§	83.1% (± 15.9) †§	83.8% (± 17.8) §	91.9% (± 12.3)
	Control	79.5% (±17.4) §	88.0% (± 13.0) §	86.8% (± 13.3) §	88.5% (± 10.5) §	84.4% (± 16.7) §

\*: Concussion group significantly lower than control group

†: Significantly less than 2 month assessment

‡: Significantly less than 2 week assessment

§: Significantly less than SAS or MAS condition

¶: Significantly less than SAS condition

Further, during the Q&A task, concussion subjects were more accurate at the two month assessment than the 72 hour, one week, and two week testing time points. Finally, both groups of subjects were less accurate on the Q&A task than the SAS or MAS tasks at the 72 hour, one week, two week, or one month time points. At the two month time point, concussion subjects were more accurate on the SAS task than the MAS task and control subjects were more accurate on the SAS and MAS tasks than the Q&A task.

### Discussion

This longitudinal and prospective investigation on dynamic balance control indicated that gait stability is affected by task complexity for adolescents following concussion. These findings are in agreement with previous work indicating that the

addition of a secondary task while walking appears to affect motor ability in young adults who suffered a concussion (128) and adults who have a history of concussion (50). The results are similar to a previous report which identified that the complexity levels of a task has a significant effect on gait in children suffering from post-severe TBI (84). In the present study, the total M/L displacement differences observed between concussion and control groups across two-months of testing in the two most complex conditions (MAS and Q&A) and within the different conditions for the concussion group, suggest that in subjects with concussion, as cognitive task complexity increases, dynamic balance control deficits increase.

The findings suggest that dual-task activities, which require complex integration, prioritization, and execution of motor and cognitive demands (168), may amplify balance disturbances in individuals suffering from concussion. Such disturbances may be reflective of incomplete physiologic recovery even though clinical symptoms may be normal (5). Further, others have used dual-task protocols and reported a regression in gait stability from a two week assessment to a one month assessment following concussion in a group of young adults who returned to pre-injury levels of activity within two weeks of injury. It was suggested that motor ability may not be sufficiently recovered despite the clinical observation of recovery (128). Subjects in the current study returned to physical activity at an average of 27 days after injury, and the mean medial/lateral velocity value increased in all walking conditions from the one month to the two month time period for the concussion group but not the control group. This may be indicative of incomplete recovery of dynamic balance control, which may not be detectable through current concussion assessment paradigms.

Neural recruitment has been reported to be the allocation of available network components based upon task demands (23) and the maintenance of balance has been suggested to require a significant amount of information processing capacity (88). Both neural recruitment and information processing abilities are required to complete a dual-task, and it has been documented that concussion may affect the ability to allocate sufficient attention to each component of a dual-task, thereby potentially resulting in the disruption of balance control (28). The data in the current study suggest these disruptions may be particularly evident under complex dual-task conditions.

The results demonstrate that individuals suffering from concussion display greater deficits to gait stability in more complex conditions while cognitive task performance differences between groups were not seen consistently across the testing time period. Hence, performance during complex dual-tasks may result in greater gait instability compared to dual-tasks of lesser complexity, potentially affected by the difficulty in information processing ability (12) or processing speed (54) following concussion, resulting in increased motor difficulty during a complex dual-task.

Previous reports have indicated that instability while walking can be detected using the motion and velocity of the COM in the frontal plane (70). In the current study however, the peak COM M/L velocity did not distinguish between groups or across time, but did between tasks suggesting that in individuals with concussion particularly, this variable may be sensitive to task complexity.

Similar to the results observed for total COM M/L displacement, peak COM anterior velocity also appeared to be sensitive to different levels of dual-task complexity in the concussion group. Peak COM anterior velocity has previously been documented as

an indicator of forward momentum control in accommodating to divided attention (28, 77). In this study, adolescents with concussion displayed a decrease in peak COM anterior velocity as cognitive task complexity increased, while control subjects did not demonstrate differences in peak COM anterior velocity in the most complex conditions (MAS and Q&A). Thus, forward momentum control during dynamic tasks, reported as a continuous regulation and integration of sensory inputs (88), may be highly affected by task complexity for adolescents with concussion.

Disruptions to cognition, such as attention and task switching ability, have been documented for a time period of up to two months following a concussion for an adolescent population (76). During this time of life, environmentally induced changes in the cortex may be detrimental to the continued development of the brain (38), making the adolescent population particularly susceptible to the effects of head trauma. Concussion-induced motor cortex disruption has been well documented following injury (7, 75, 154) and may be a contributor to gait imbalance following concussion.

Proper attentional distribution is considered especially needed to perform multiple tasks when the system is near its limits (168) and the failure to flexibly switch between tasks or to distribute attention across tasks may occur in those suffering from brain trauma (47). As attentional disruptions may be particularly susceptible to the effects of concussion (45), and individuals suffering from concussion have difficulties in orienting attention (48) or other decreased attentional abilities (100), increased task complexity may require prioritization; this may result in the inability to complete both tasks with equal success.



Dual-tasks have been indicated in the management of concussion (156) and reported as a way to detect subtle neurological deficits associated with concussion (92). If motor and cognitive capacities are limited, at least one of them may deteriorate when performed simultaneously (167). As the applicability of dual-task assessments in the clinical management of concussion has recently been documented as a way to increase sensitivity to subtle deficits following injury (143), this type of testing may provide an additional tool through which accurate assessment of recovery from concussion can occur. Further, the utilization of more complex tasks in dual-task scenarios may be able to better detect subtle neurological deficits beyond traditional testing techniques, and more sensitively identify complete recovery following concussion.

#### *Study Limitations*

While the prospective and longitudinal design of this study allows for the monitoring of an acutely injured individual from a time period immediately after the injury and through the two months following the injury, the severity of injury for each individual may have varied highly. Previous reports have included concussion grading as an attempt to quantify injury severity (26), however more recent literature has abandoned grading scales in order to individually guide return to activity decisions following injury (110). The study was also limited as no subject baseline data were available for analysis. Consistent with previous work (76), the inclusion of individually matched healthy control subjects to which the sample of concussion subjects was compared to for the same testing protocol and timeline countered this limitation to some extent.

## Conclusion

Dual-tasks of varying complexity appear to affect gait balance control in adolescents recovering from concussion, particularly on tasks with greater complexity. Varying dual-task complexity represents a useful way to identify motor or cognitive recovery following concussion, and may assist clinicians in the management and recovery monitoring following concussion.

## Bridge

Chapter IV summarized the effects of cognitive task complexity performed during a dual-task walking assessment following concussion. As Chapters II – IV have each examined the effects of concussion on a group of individuals from the time of injury through the subsequent two months post-injury, the way recovery was affected by behavioral factors, such as returning to physical activities, for each individual remains unknown. Thus, Chapter V examines how timing of return to activity post-concussion affects gait balance control recovery in order to identify how recovery may be altered by participation in such activities.

## CHAPTER V

### STUDY 4: RETURN TO ACTIVITY AFTER CONCUSSION AFFECTS DUAL-TASK GAIT BALANCE CONTROL RECOVERY

This study has been co-authored with Louis Osternig and Li-Shan Chou and has been submitted for publication. David Howell contributed to the concept of the study, recruited subjects, coordinated and supervised data collection, wrote analysis software, performed initial data analysis and statistical analysis, and prepared the initial manuscript. Louis Osternig and Li-Shan Chou contributed to the concept of the study, the analysis and interpretation of the data, and critically reviewed and revised the manuscript.

#### Introduction

Much attention has been given in recent years to the issue of diagnosis, treatment, and management of concussion. Grading scales have been used to quantify injury severity and guide protocols related to return to physical activity, however these have been discarded gradually as such scales may not fully encompass the physiological disturbances and consequent resolution induced by a concussive event (111). Current best-practice treatment protocols include a period of complete physical and cognitive rest immediately after injury followed by a stepwise reintegration into pre-injury activities once symptoms have resolved, and cognitive and balance functions return to pre-injury levels (73, 113). Although previous investigations have revealed a vast amount of information regarding the pathophysiology of concussion (40, 60), the decision of when

an individual returns to physical or cognitive activities following concussion remains among the most difficult and controversial issues in clinical sports medicine (46). Despite recent efforts by state (157) and various professional associations (46), no consistent regulations currently exist for timing of return to pre-injury activities.

Various concussion position statements have discussed elements used in the decision of when to begin the resumption of physical activities (73, 111, 112), while other studies have addressed the relationship between concussive impacts and healing rates (13), and the time course of physiologic recovery after concussion (133). However, no investigations have systematically examined how resuming pre-injury levels of activity affects cognitive and motor function. Barr and colleagues have reported that physiological recovery may extend beyond clinically observed recovery (5), suggesting that traditional testing techniques may not be sufficiently sensitive to detect subtle deficits following concussion. As it has been documented that football players who sustain a concussion are up to three times more likely to sustain a second within the same season compared with those who have not sustained a concussion (67), premature return to play may be one potential factor in such increased vulnerability.

A period of metabolic vulnerability in brain tissue has been reported to occur following a concussive event (60), as well as alterations to cerebral blood flow (104), neurochemical impairments (158), and electrophysiological deficits (133), all which may contribute to symptom generation and other neurologic dysfunction. A fMRI investigation also revealed that despite similar working memory performance for concussion subjects compared with a cohort of matched controls, brain activation differences were still present at two months following concussion (43). Other recent

work has identified cognitive deficits in concussion subjects compared to healthy subjects for up to two months post-concussion on measurements of attention and task switching (76). Due to these various impairments to the brain following injury, a secondary insult of modest intensity may cause further impairment to neuronal function (60, 169) and thus prolong the recovery process (158). These pathological changes to the brain following injury underlie the current recommendation to refrain from exercise following concussion, until cleared by a physician to do so (112).

One method to assess recovery following concussion is to measure gait balance control during dual-task walking (77, 128). Gait stability during dual-task walking may be particularly sensitive to long term disruptions following concussion and has been suggested to be a well suited variable for sensitive detection of pathological behavior related to concussion (50, 103). This type of test employs attention-demanding, high-level ability (168), and when used to identify the duration of motor impairments following concussion, revealed that deficits to gait balance control were present across two months of testing post injury (77). However, the role return to activity played in these results is unknown. Using a dual-task protocol, Parker et al. (2006), reported a significant regression in gait stability from a two week assessment to a one month assessment following concussion in a group of young adults who returned to activity within two weeks of the injury (128). It was suggested that motor ability may not have been sufficiently recovered prior to returning to activity and may have been influenced by enhanced susceptibility to the effect of brain injury resulting from the return to physical activity.

Despite the lack of a current gold standard for the clearance of individuals to return to physical activity following concussion, healthcare professionals are nonetheless asked to provide such clearance. This remains a challenging task despite many recent protocol developments (46). Further complicating this clinical decision is the vulnerability of the injured person to a second concussion (79) and the possibility that premature return to physical activity may increase the risk of re-injury or prolong recovery. Therefore, the purpose of this study was to prospectively and longitudinally examine a cohort of adolescents who returned to activity within two months of injury, and to observe how the return to physical activity affects recovery from concussion. This was done by examining adolescents with concussion prior to and after returning to pre-injury activities on measures of cognition, symptom severity, and balance control during single-task and dual-task walking. It was hypothesized that following concussion, returning to physical activities within 2 months post-injury would disrupt dual-task walking recovery to a greater degree than symptom recovery, cognitive recovery or single-task walking recovery.

## Methods

### *Subject Identification*

Subjects who sustained a concussion were diagnosed and identified for potential inclusion in the study by a healthcare professional (certified athletic trainer or physician). Concussion diagnosis was defined according to McCrory et al (111) as an injury caused by a direct blow to the head, face, neck, or elsewhere on the body with an impulsive force transmitted to the head, resulting in impaired neurologic function and acute clinical

symptoms. Each subject who was enrolled in the study following a concussion was matched with a healthy control subject by sex, height, mass, age, and sport.

Prior to data collection, the institutional review board reviewed and approved the study protocol. All subjects and parents/guardians (if under the age of 18) provided written consent to participate in the study. Permission was also granted by the respective school districts to conduct testing with student participants.

Each subject who sustained a concussion was removed from the injury site on the day of the injury and did not return to any physical activities or pre-injury levels of participation until cleared by a physician in accordance with state law. Concussion management decisions regarding the return to activity day were made independent from the study by attending physicians. Exclusion criteria for all prospective subjects included the following: 1) lower extremity deficiency or injury, which may affect normal gait patterns; 2) history of cognitive deficiencies, such as permanent memory loss or concentration abnormalities; 3) history of three or more previous concussions; 4) loss of consciousness from the concussion lasting greater than one minute; 5) history of attention deficit hyperactivity disorder; or 6) a previously documented concussion within the past year. Consistent with previous work (76), individuals with three or more previous concussions were ineligible to participate in the study to ensure, to the extent possible, the exclusion of subjects experiencing chronic mild traumatic brain injury (mTBI) and those who experienced a loss of consciousness for greater than one minute were excluded because of the role this sign plays in concussion management modification (111). A verbal medical history was taken by a certified athletic trainer for all subjects upon their first visit to the laboratory to confirm all criteria were met for inclusion in the study.

### *Testing Time Points*

A prospective, repeated measures design was employed in which each subject reported to the laboratory and was tested at 5 time points: within 72 hours of sustaining a concussion as well as approximately one week, two weeks, one month, and two months post-injury. Control subjects were initially assessed and then tested similarly according to the same testing schedule as concussion subjects.

The return to activity (RTA) day for concussion subjects was documented as the first day after injury in which participation in physical activities was allowed by the attending physician or healthcare provider and was self-reported. Consistent with Prichep et al. (133), decisions for the RTA day were made by attending healthcare professionals using conventional methods and were made independent of study-related data. The concussion subjects who returned to physical activity within the two months of testing were analyzed in the current study along with their individually matched control subjects.

In this study, it was necessary to control for variability of the RTA day within the group of concussion subjects. To achieve this, the effect of returning to physical activity was assessed by evaluating the percent change ( $\% \Delta$ ) in the dependent variables (identified below) for each concussion subject between specific testing time points both before (pre RTA) and after (post RTA) the return to activity day. The specific time points were: 1) two time points prior to the return to activity day (pre-return 2); 2) one time point prior to the return to activity day (pre-return 1); and 3) one time point after the return to activity day (post-return 1).



The pre RTA percent change (from pre-return 2 to pre-return 1) and post RTA percent change (from pre-return 1 to post-return 1) were calculated according to the following:

$$\% \Delta \text{ Pre RTA} = (\text{pre-return 1} - \text{pre-return 2} / \text{pre-return 1});$$

$$\% \Delta \text{ Post RTA} = (\text{post-return 1} - \text{pre-return 1} / \text{pre-return 1}).$$

Data from each control subject were evaluated at the same time points as their matched concussion counterpart.

### *Dependent Variables*

All subjects were assessed on measures of balance control of single-task and dual-task walking, cognition, and clinical symptoms, detailed in previous investigations (76, 77). During gait analysis, subjects walked barefoot at a self-selected speed along a level walkway under two conditions: walking with undivided attention (single-task) and walking while concurrently completing a continuous auditory Stroop test (dual-task). The continuous Stroop test consisted of the subject listening to four auditory stimuli while walking: the recorded words “high” or “low”, each spoken in a high or low pitch. Subjects were instructed to correctly identify the pitch of the word, regardless of whether the pitch was congruent with the meaning of the word. Each of the four stimuli was presented in random order at a specific time while walking. The first stimulus was presented once subjects had achieved steady state gait and was triggered by a photocell located several steps after gait initiation. Each of the three subsequent stimuli was presented one second after the previous response while the subject continued to walk. Subjects were not instructed to focus attention specifically on either the walking task or the cognitive task, but to continue walking while correctly responding to each stimulus.

Eight to ten consecutive trials were completed for each of the conditions (single-task and dual-task).

A set of 29 retro-reflective markers were placed on bony landmarks of the subject (69), and whole body motion analysis was performed using a 10-camera motion analysis system (Motion Analysis Corp., Santa Rosa, CA) at a sampling rate of 60Hz to capture and reconstruct the three-dimensional trajectory of each marker. Marker trajectory data were low-pass filtered using a fourth-order Butterworth filter with a cutoff frequency set at 8Hz. Whole body center of mass (COM) position data were then calculated as the weighted sum of all body segments, with 13 segments representing the whole body. For each trial, data were analyzed for one gait cycle, defined as heel strike to heel strike of the same limb. During the gait cycle, the range of medial/lateral COM displacement was obtained. The anterior and medial/lateral linear COM velocities were calculated using the cross-validated spline algorithm from COM positions (163), and the peak velocities in both directions were identified. Individuals suffering from a concussion have previously been reported to exhibit a greater and faster COM motion in the frontal plane with a reduced sagittal plane motion compared with matched controls (77, 128). A reduction (negative %  $\Delta$  value) in medial/lateral COM displacement and velocity variables indicates improvement of gait balance control from one time point to the next, while an increase (positive %  $\Delta$  value) indicates a worsening of gait balance control from one time point to the next. In contrast, a positive %  $\Delta$  peak anterior COM velocity value indicates improvement from one time point to the next, while a negative %  $\Delta$  peak anterior COM velocity value indicates a worsening between time points.

Assessment of cognitive function was performed using two computerized tests: the Attention Network Test (53, 76) and the Task Switching Test (76, 107). The ANT probes the efficiency of three distinct components of attention: alerting, spatial orienting, and conflict resolution, and has been investigated in this subject population previously (76). For this test, the subject fixates on a cross in the center of a computer screen and responds as quickly and accurately as possible by pressing one of two arrow keys, indicating the direction of a central arrow presented directly above or below the cross (target arrow). The target arrow is accompanied by two flanker arrows positioned on either side of the target arrow, which may point in the same or opposite direction of the target arrow. The primary dependent variable investigated was the conflict effect, which is measured as the accurate response median reaction time difference between two conditions: trials in which the target arrow is accompanied by two congruent flanker arrows (arrows pointing in the same direction) versus trials in which the arrow stimulus is accompanied by two incongruent flanker arrows (arrows pointing in the opposite direction). The conflict effect probes conflict resolution, and a greater RT difference score between groups/testing days indicates poorer performance in the ability to resolve conflict. A reduction (negative %  $\Delta$  value) on the conflict effect variable indicates improvement of conflict resolution ability from one time point to the next, while an increase (positive %  $\Delta$  value) indicates a worsening from one time point to the next.

The TST specifically tests the ability to flexibly switch between competing task or stimulus-response rules (142) and has also been investigated in this subject population previously (76). Subjects are required to switch between responding congruently and incongruently to the position of a visual stimulus on a computer screen on every second

trial in a sequence. Within each trial, the subject responds to the position of a circle presented in a horizontally configured rectangular box by pressing the right or left arrow key on a standard computer keyboard as quickly and accurately as possible, according to the specific rules of the test. For the congruent trials rule, subjects press the arrow key corresponding to the left or right position of the circle inside the rectangle for two consecutive trials. The incongruent trials rule begins on the next trial, which requires the subject to switch to pressing the arrow key which is opposite to the position of the inside the rectangle for two consecutive trials. Hence, the subject switches rules every two trials (congruent-congruent/incongruent-incongruent). The primary dependent variable, the switch cost, measures the response time difference between trials on which the task changes (switch trials) and trials on which the task stays the same (no-switch trials). A higher switch cost indicates greater difficulty in adhering to the congruent/incongruent rules. A reduction (negative %  $\Delta$  value) on the switch cost indicates improvement of task switching ability from one time point to the next while an increase (positive %  $\Delta$  value) indicates a worsening of task switching ability from one time point to the next.

Clinical symptoms were assessed at each visit to the laboratory using a 22-symptom inventory adapted from the Standardized Concussion Assessment Tool version 2 (SCAT2) (111), with each symptom ranked on a Likert scale from 0 to 6, resulting in a range of scores from zero (no symptoms) to 132 (maximum severity on all symptoms). Absolute change values were calculated for symptom scores for pre and post RTA. A negative change value indicates fewer symptoms reported from one time point to the next and therefore an improvement in symptom score, while a positive change value indicates

an increase symptoms reported from one time point to the next and therefore a worsening in clinical symptom score.

### *Statistical Analysis*

Data were analyzed by two-way mixed effects analyses of variance for each dependent variable in order to determine the effect of group (concussion and control) and time (pre RTA and post RTA) and the interaction between the two. For all omnibus tests, significance was set at  $p < .05$ . Follow-up pairwise comparisons were examined using the Bonferroni procedure to control family wise type I error and reported with  $p$  values corrected in this way. All statistical analyses were performed with SPSS version 20.

## Results

### *Subjects*

Twenty-five local high school students who suffered a concussion while participating in school sports and 25 individually matched control subjects completed the study protocol. Of the 25 subjects who sustained a concussion, 19 individuals (16 males/3 females) returned to physical activity within the two months of testing following the injury yielding 19 pairs of concussion and control data used for study analyses. Six of the 25 subjects with concussion did not return to physical activity within two months post-injury and their data were not used in the study.

No significant demographic differences were observed between the concussion and control groups for age, height, or mass ( $p > .65$ ; Table 8). Concussion subjects were assessed at  $2 \pm 0.7$ ,  $8 \pm 1.8$ ,  $17 \pm 3.8$ ,  $30 \pm 2.8$ , and  $58 \pm 2.3$  days after injury. Control subjects underwent an initial assessment and also at  $7 \pm 1.8$ ,  $16 \pm 4.7$ ,  $30 \pm 3.5$ , and  $57 \pm$

6.4 days after the initial assessment. No subject reported sustaining a concussion during the testing period. The mean RTA day for all concussion subjects who returned to physical activity within the two months of testing was 23.5 ( $\pm$  14.4) days post-injury.

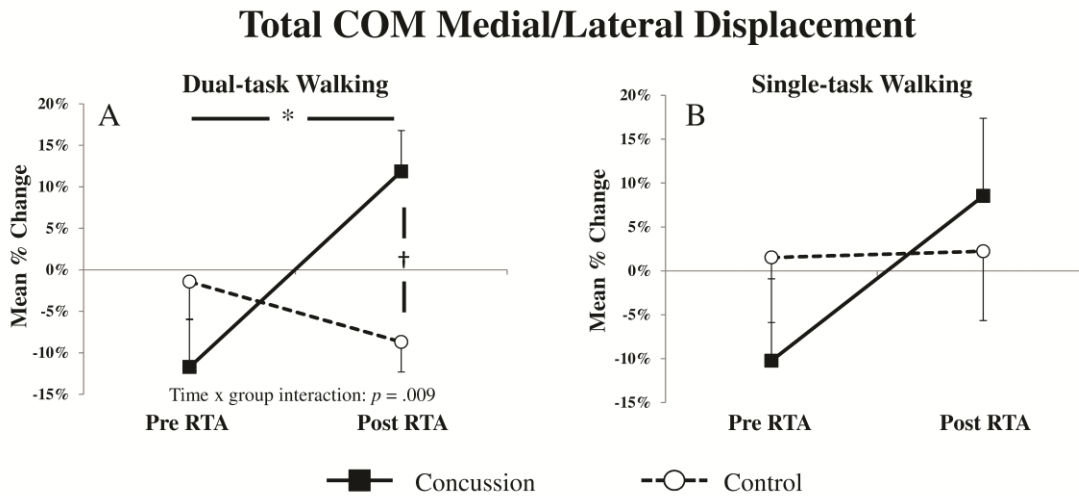
**Table 8:** Demographic information for the concussion and control groups (mean  $\pm$  SD).

Characteristics	Concussion Group	Control Group
Sex ( <i>n</i> )	16 male/3 female	16 male/3 female
Age (years)	15.4 ( $\pm$ 1.4)	15.6 ( $\pm$ 1.1)
Height (cm)	171.7 ( $\pm$ 5.8)	172.3 ( $\pm$ 8.3)
Weight (kg)	67.6 ( $\pm$ 10.1)	68.6 ( $\pm$ 13.3)
Sport ( <i>n</i> )	Football: 13 Soccer: 4 Wrestling: 1 Volleyball: 1	Football: 13 Soccer: 3 Wrestling: 1 Volleyball: 1 Basketball: 1
RTA (days post-injury)	25.3 ( $\pm$ 14.4)	N/A

#### *Dual-Task Walking*

A significant group x time interaction was observed for the changes in dual-task COM medial/lateral displacement [ $F(1, 36) = 7.65, p = .009, \eta_p^2 = .175$ ; Figure 10A]. A mean pre RTA decline of 11.7% in medial/lateral displacement was found for the concussion group, suggesting improved COM control from pre-return 2 to pre-return 1 time points. However, a mean post RTA increase of 11.8% for this variable was observed in the concussion group, which was significantly different than the pre RTA change, suggesting significant worsening of COM control over the post RTA period

(follow-up comparison:  $p = .005$ , mean difference = 23.6%; Figure 10A). The concussion group mean post RTA %  $\Delta$  in medial/lateral displacement was also significantly greater than that of the controls for the same time point measurements (follow-up comparison:  $p = .002$ , mean difference = 20.5%; Figure 10A).



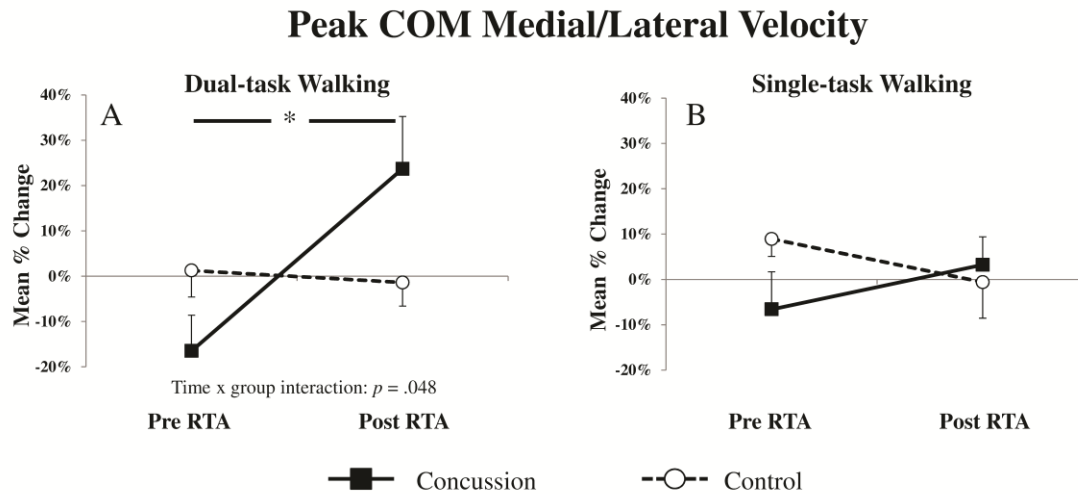
**Figure 10:** Total COM medial/lateral displacement pre and post RTA %  $\Delta$  (mean  $\pm$  standard error). For concussion subjects, results indicated an improvement during dual-task walking pre RTA while demonstrating a worsening of COM frontal plane motion control post RTA (A). No significant results were detected during single-task walking (B).

\* : Significant difference between time periods for the concussion group.

† : Significant difference between concussion and control groups.

Analysis of the peak COM medial/lateral velocity during dual-task walking also revealed a significant group x time interaction [ $F(1, 36) = 4.20, p = .048, \eta_p^2 = .104$ ; Figure 11A]. The mean pre RTA %  $\Delta$  for concussion subjects was -16.5%, suggesting improved control of peak COM medial/lateral velocity from pre-return 2 to pre-return 1 time points. Similar to the medial/lateral displacement findings, a mean post RTA increase of 23.9% in medial/lateral velocity was observed in the concussion group, which

was significantly different than the pre RTA value, suggesting worsening of COM velocity control over the post RTA period (follow-up comparison:  $p = .010$ , mean difference = 40.2%; Figure 11A). No significant findings were observed for the control group.

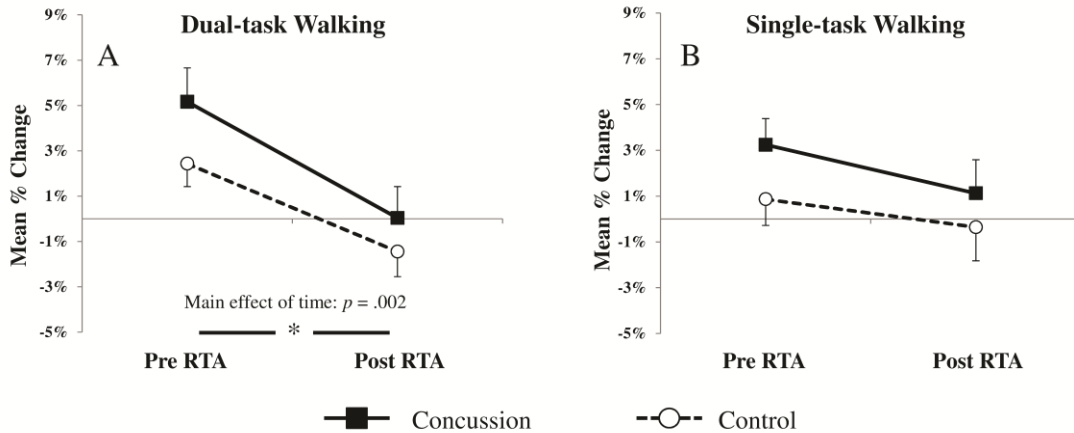


**Figure 11:** Peak COM medial/lateral velocity pre and post RTA %  $\Delta$  (mean  $\pm$  standard error). During dual-task walking, concussion subjects demonstrated a reduction in frontal plane velocity pre RTA, suggesting an improvement while an increase in frontal plane COM velocity was observed post RTA, indicating a worsening of COM frontal plane velocity (A). No significant results were detected during single-task walking (B). \* : Significant difference between time points for the concussion group.

The results for peak COM anterior velocity during dual-task walking showed a main effect of time [ $F(1, 36) = 11.13, p = .002, \eta_p^2 = .236$ ; Figure 12A] and indicated a significant decrease in the %  $\Delta$  of peak COM anterior velocity between pre RTA and post RTA time periods. No significant between-group differences were detected for this variable.



## Peak COM Anterior Velocity



**Figure 12:** Peak COM anterior velocity pre and post RTA %  $\Delta$  (mean  $\pm$  standard error). Results indicated both groups of subjects demonstrated an improvement in sagittal plane velocity control pre RTA and very little change post RTA during dual-task walking (A). No significant results were found for single-task walking (B).  
\* : Significant difference between time points for both groups of subjects.

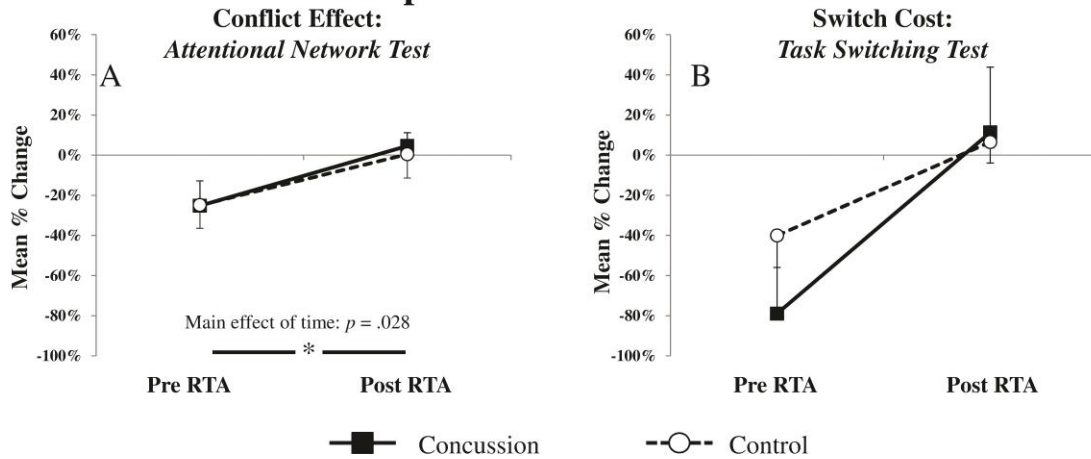
### *Single-Task Walking*

The total COM medial/lateral displacement, peak COM medial/lateral velocity, and peak COM anterior velocity data during single-task walking revealed no significant interactions or main effects (Figures 10B, 11B, and 12B).

### *Cognitive Tests*

Analysis of the conflict effect variable of the ANT revealed a main effect of time [main effect of time;  $F(1, 36) = 5.25$ ,  $p = .028$ ,  $\eta_p^2 = .127$ ; Figure 13A]. The mean pre RTA %  $\Delta$  for both groups of subjects was -25.1%, indicating an improvement in conflict effect scores from pre-return 2 to pre-return 1 time points. The mean post RTA %  $\Delta$  for both groups was 2.5%, indicating little change between pre-return 1 and post-return 1 time points. However, no between group differences were found for the conflict effect. Switch cost analysis revealed no main effects of group, time, or interactions between the two (Figure 13B).

## Computerized Tests of Attention

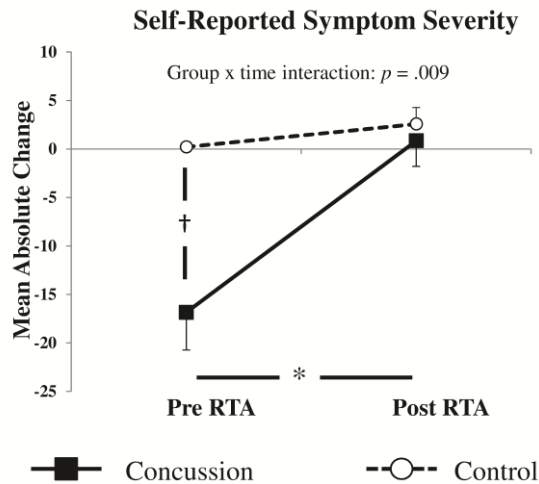


**Figure 13:** Computerized attention testing pre and post RTA %  $\Delta$  (mean  $\pm$  standard error). Results indicated both groups of subjects demonstrated an improvement on the conflict effect variable pre RTA and a very little change post RTA (A). No significant results were found for the Task Switching Test (B).

\* : Significant difference between time points for both groups of subjects.

### *Clinical Symptoms*

The evaluation of pre and post RTA changes in symptom scores revealed a significant group x time interaction [ $F(1, 36) = 7.55, p = .009, \eta_p^2 = .173$ ; Figure 14]. The mean pre RTA change was -16.8 for concussion subjects, indicating an improvement of clinical symptoms from the pre-return 2 to pre-return 1 time points. This value was significantly greater than that of the controls (follow-up comparison:  $p < .001$ , mean difference = 17.1) who showed very little change for either testing interval (Figure 5). Follow-up comparisons for the concussion group indicated that the mean pre RTA and the mean post RTA changes were significantly different (follow-up comparison:  $p < .001$ , mean difference = 17.7), however the mean post RTA change was 0.8, suggesting clinical symptom stability following RTA (Figure 14).



**Figure 14:** Self-reported symptom severity inventory pre and post RTA changes (mean  $\pm$  standard error). Results indicated that concussion subjects decreased their symptom severity pre RTA while demonstrating very little change post RTA. Control subjects demonstrated no significant symptom severity changes.

\* : Significant difference between time points for the concussion group.

† : Significant difference between concussion and control groups.

### Discussion

The findings from this study indicate that pre RTA, concussion subjects reduced their medial/lateral displacement and velocity during dual-task walking, suggesting an improvement in gait balance control, while significantly increasing these frontal plane motion variables during dual-task walking post RTA, suggesting a worsening of frontal plane COM control following RTA. However, similar comparisons for clinical symptoms, single-task walking, COM forward velocity, and cognition indicated improvement or stability in both groups across the same testing time periods. These data suggest that frontal plane motion during dual-task walking may be more sensitive to the effects of return to activity following concussion than sagittal plane measurements, single-task walking, cognitive functions, or clinical symptoms, and may reveal a possible regression in gait stability following return to activity.

A recent investigation by Teel et al (2013) found that subjects who sustained a concussion in the past week performed at the same level as control subjects on traditional cognitive assessments, while still exhibiting pathological dysfunction of brain electrical activity. It was suggested that current tools used to assess return to activity following concussion may not possess the required sensitivity to detect such deficits after injury (155). It has been suggested by others that static balance ability (132) and dynamic balance control (128) may not be fully recovered prior to the decision to return athletes to activity. Dual-task assessments have been explored as a means to evaluate the readiness for functional return to sport activity (138) or military duty decisions (144) and the incorporation of a cognitive task while simultaneously performing a motor task has been reported to increase the sensitivity of concussion resolution detection, compared with a single-task motor assessment (143). These studies are in agreement with the data presented in the current study which suggest that dynamic balance control may require a longer period of time to recover than standard clinical tests used to determine the timing of return to activity.

Previous work has identified impairments to gait balance control through analyses of frontal and sagittal plane COM motion in elderly individuals as well as in individuals with concussion (69, 77, 128). However, in the current study, the cohort of adolescents with concussion demonstrated a regression of recovery in frontal plane COM motion control post RTA, while very little change occurred in sagittal plane movement post RTA. This suggests that frontal plane motion variables may be more sensitive detectors of gait imbalance following concussion than sagittal plane parameters. Frontal plane motion appears to be particularly well suited to provide information about the ability to

control whole body motion and potentially identify those who are at risk for imbalance (70, 77). A regression in recovery of side-to-side motion control associated with return to activity following concussion could potentially affect vulnerability to further injury.

In the present investigation, the ANT and TST cognitive assessments revealed that both the concussion and control subject scores improved during the pre RTA period and remained stable post RTA. This suggests a possible learning effect occurred pre RTA in both groups, which diminished post RTA as no appreciable change was noted from pre-return 1 to post-return 1 time points for either group. The explanation for this finding is indefinite. It is possible that the subjects had reached a learning curve asymptote by pre-return 1, which was not affected by return to activity, or that the improvement noted in pre RTA was interrupted by return to activity. Previous work reported learning effects for the ANT and TST for adolescents with concussion and matched control subjects over two weeks post-injury (76). Although a significant between-group raw score difference remained over two months post-injury, the effect of return to activity was not analyzed in that study. In the current study, no changes were seen in the rate of improvement between groups.

Results indicated a significant improvement for concussion group self-reported symptom severity scores pre RTA but very little symptom severity change post RTA. As the mean post RTA change for concussion subjects was near zero (mean = 0.8), it appears that RTA did little to elicit either positive or negative changes in symptom severity. Thus, the self-reported symptom severity for concussion subjects may not be affected by the RTA, in contrast to frontal plane movement during dual-task walking, which was negatively affected by RTA. Consistent with other literature, this result suggests that

objective assessment techniques may reveal longer lasting post-concussive features than subjective symptom reporting (15, 76). Further, a previous study has identified gait stability worsening from two weeks to one month post-injury in a group of collegiate athletes who each returned to their sport within two weeks of injury despite not reporting a second concussion (128). Other studies have concluded that traditional methods used to determine return to activity timing may not possess sufficient sensitivity to detect concussion-related abnormalities that persist beyond symptom or clinical resolution (133, 155). Thus, returning to activity when recovery is not complete may exacerbate deficits related to incomplete recovery and may result in the worsening of frontal plane motion control observed during dual-task walking.

#### *Study Limitations*

The potential variability among healthcare professionals in assessing concussion recovery possibly influenced the timing of return to activity. Although current best practice indicates a period of cognitive rest following concussion (112), which has been shown to be effective in decreasing the time required to achieve symptom recovery (22), the amount of cognitive activity each subject was exposed to following injury is unknown.

#### Conclusion

Following the return to activity after concussion, subjects with concussion displayed increased medial/lateral COM displacement and velocity during dual-task walking, suggesting a regression of recovery in gait balance control. This study reinforces the need for a multi-faceted approach to concussion management and

continued monitoring beyond the point of clinical recovery and the resumption of physical activities.

### Bridge

Data presented in Chapters II – V have included analyses of adolescent athletes. As the way that concussion affects individuals across the age spectrum and throughout brain development still requires further investigation (73), it is important to examine adolescent gait balance control recovery post-concussion in comparison with older individuals. Thus, Chapter VI presents an examination of gait balance control deficits for adolescents and young adults with concussion in comparison to a matched and healthy control group will help to identify the way individual recovery occurs and assist in the individualized and multifaceted approach to concussion management.

## CHAPTER VI

### STUDY 5: ADOLESCENTS DEMONSTRATE GREATER GAIT BALANCE CONTROL DEFICITS AFTER CONCUSSION THAN YOUNG ADULTS

This study has been co-authored with Louis Osternig and Li-Shan Chou and has been submitted for publication. David Howell contributed to the concept of the study, recruited subjects, coordinated and supervised data collection, wrote analysis software, performed initial data analysis and statistical analysis, and prepared the initial manuscript. Louis Osternig and Li-Shan Chou contributed to the concept of the study, the analysis and interpretation of the data, and critically reviewed and revised the manuscript.

#### Introduction

The management of concussion has evolved considerably over the past several years. Although concussion severity grading scales were traditionally employed to guide management decisions, they have now been abandoned in favor of an individualized approach to concussion management based on a multi-faceted evaluation of function (117). Best-practice treatment statements have identified age as a treatment modifier, recommending that younger populations who sustain a concussion be managed in a conservative manner (73, 112). Traumatic brain injury (TBI) has been reported to affect a developing brain differently than a fully developed brain, suggesting that adolescents may have a more complicated recovery than adults (112, 119).

Adolescence is a critical time of brain development and brain injury during this stage of life may result in greater degree of injury than for an adult (4, 66). In addition to



developmental differences, anatomical and physiological differences such as brain water content, degree of myelination, skull shape, cerebral metabolic rate of glucose, and total number of synapses have been identified as possible mechanisms which may help to explain adolescent vulnerability to concussion-related effects (66, 73, 119). The mechanics of the concussive event may also affect injury-related outcomes. High school and collegiate football players appear to undergo similar levels of head acceleration during impact (17), but due to the immaturity of the musculoskeletal system, younger athletes may possess a diminished ability to control the head and reduce head acceleration following impact, potentially leading to increased stress of brain tissue (17).

Previous research has revealed various concussion-related effects through neuropsychological testing (55, 108), attentional testing (71, 76), static balance testing (16, 132), and dynamic balance testing (77, 128). Dual-task assessments in particular have been reported to provide a sensitive detection of persistent neurological deficits following a concussion (92, 103). The Stroop test has been documented as a secondary task in a dual-task paradigm which provides conflict-resolution information, previously shown to be affected by concussion (30, 71, 76). Thus, an examination of dual-task gait balance control may provide information about multi-task ability in daily activities following concussion (77, 78).

Although the developing brain may react to an injurious event differently than an adult (66), comparisons of motor function deficits following concussion between adolescent and adult age groups have yet to be reported. Therefore, the purpose of this study was to prospectively and longitudinally examine how adolescents and young adults with concussion perform on measures of gait stability during dual-task walking in

comparison to matched control subjects within 72 hours post-injury and systematically throughout two months post-injury. It was hypothesized that adolescents with concussion would display greater gait balance control deficits than young adults with concussion in relation to matched control subjects 72 hours post-injury, and such deficits would require a longer duration of time to reach a level similar to control subjects for adolescents than young adults.

## Methods

### *Subject Identification*

High school and college students who sustained a concussion were diagnosed and identified for potential inclusion in the study by a certified athletic trainer or physician. The definition of concussion was consistent with McCrory et al (111): an injury caused by a direct blow to the head, face, neck, or elsewhere on the body with an impulsive force transmitted to the head, resulting in a graded set of clinical symptoms. Each subject with concussion enrolled in the study was matched with a healthy control subject by sex, height, mass, age, and activity participation.

Prior to data collection, the institutional review board reviewed and approved the study protocol. All subjects and parents/guardians (if under the age of 18) provided written consent to participate in the study. Permission was also granted by the respective high school districts and colleges/universities to conduct testing with student participants. Exclusion criteria for all prospective subjects included the following: 1) lower extremity deficiency or injury, which may affect normal gait patterns; 2) history of cognitive deficiencies, such as permanent memory loss or concentration abnormalities; 3) history of

three or more previous concussions; 4) loss of consciousness from the concussion lasting greater than one minute; 5) history of attention deficit hyperactivity disorder; or 6) a previously documented concussion within the past year. Consistent with previous work, potential subjects were not included in the study with three or more previous concussions to ensure, to the extent possible, those with chronic mild traumatic brain injury were not a part of the study (76, 77). Additionally, those who experienced a loss of consciousness for greater than one minute were excluded because of the role that this sign plays in concussion management modification (112). A verbal medical history was taken by a certified athletic trainer with each subject upon their first laboratory visit to confirm all criteria were met for inclusion in the study. Concussion management decisions for all subjects in the study were made independently from the study by attending physicians.

#### *Testing Timeline*

A prospective, repeated measures design was employed where subjects with concussion reported to the laboratory within 72 hours post-injury as well as approximately one week, two weeks, one month, and two months post-injury. Control subjects were initially assessed and then tested similarly according to the same testing schedule as concussion subjects.

#### *Protocol*

All subjects were evaluated on measures of balance control during dual-task walking. During the assessment, subjects walked barefoot at a self-selected speed along a walkway while completing an auditory Stroop test. The Stroop test consisted of the subject listening to four auditory stimuli: the recorded words “high” or “low” spoken in either a high or low pitch. Subjects were instructed to identify the pitch of the word,

regardless of whether the pitch was congruent with the word. Each of the four stimuli was presented in random order at a specific time while walking. The first stimulus was presented once the subject had achieved steady state gait and was triggered by a photocell located several steps after gait initiation. Each of the three subsequent stimuli was presented one second following the previous response while the subject continued to walk. Subjects were not instructed to focus attention specifically on either the walking task or the Stroop test, but to continue walking while correctly responding to each stimulus. Eight to ten consecutive trials were completed at each testing session.

A set of 29 retro-reflective markers were placed on bony landmarks of the subject (69) and whole-body motion analysis was performed using a 10-camera motion analysis system (Motion Analysis Corp., Santa Rosa, CA) at a sampling rate of 60Hz to capture and reconstruct the three-dimensional trajectory of each marker. Marker trajectory data were low-pass filtered using a fourth-order Butterworth filter with a cutoff frequency set at 8Hz. Whole body center-of-mass (COM) position data were then calculated as the weighted sum of all body segments, with 13 segments representing the whole body.

The dependent variables for this study were derived from previous research, which identified dynamic balance control indicators from COM movement during walking in elderly individuals (69), those suffering from TBI (6), young adults with concussion (128), and adolescents with concussion (77, 78). For each trial, motion data were analyzed for one gait cycle, defined as heel strike to heel strike of the same limb. The balance control variables included total medial-lateral COM displacement and the peak instantaneous COM velocity in the medial-lateral and anterior directions. The medial-lateral and anterior linear COM velocities were calculated using the cross-

validated spline algorithm from COM positions (163) and the peak velocities in both directions were identified.

Clinical symptoms were assessed at each laboratory visit using a 22-symptom inventory adapted from the Standardized Concussion Assessment Tool Version 2 (111) with each symptom ranked on a Likert scale from 0 to 6, resulting in a range of scores from 0 to 132.

Demographic data were analyzed by one-way analyses of variance. Each dependent variable (total medial-lateral COM displacement, peak medial-lateral COM velocity, peak anterior COM velocity, and clinical symptom severity) was evaluated: 1) to determine if differences existed between groups within 72 hours post-injury, and 2) to examine how each group performed across the two months post-injury. Within 72 hour post-injury data were analyzed using one-way analyses of variance in order to determine differences between each group. Data related to performance across the two months post-injury were analyzed via two-way mixed effects analyses of variance in order to determine the effect of group, time, and the interactions between these independent variables. For all omnibus tests, significance was set at  $p < .05$ . Follow-up pairwise comparisons were performed using the Bonferroni procedure to control family wise type I error, in order to compare groups of the same age (young adult concussion vs. young adult control; adolescent concussion vs. adolescent control) and concussion/healthy groups (young adult concussion vs. adolescent concussion; young adult control vs. adolescent control). All statistical analyses were performed with SPSS version 20.

## Results

### *Subjects*

Thirty-eight individuals who sustained a concussion and 38 individually matched control subjects completed the study protocol. Of the 38 subjects in the concussion group, 19 were young adults (age range 18–27 years) and 19 were adolescents (age range 14 – 17 years; see Table 9). Consistent with the study design, a significant effect of age was observed between the groups [ $F(3, 75) = 52.3, p < .001, \eta^2 = .686$ ], as young adult groups were significantly older than adolescent groups ( $p < .001$ ). No significant effects were detected for body height or mass.

**Table 9:** Mean ( $\pm$  SD) demographic data for each subject group.

Group	Sex ( <i>n</i> )	Age (Years)	Age Range	Height (cm)	Mass (kg)	Mechanism of Injury ( <i>n</i> )
Young Adult Concussion	10 F / 9 M	20.3 ( $\pm 2.4$ )*	18-27	171.5 ( $\pm 9.5$ )	71.8 ( $\pm 15.4$ )	Activities of daily living: 5 Bike accident: 4 Sport (head – opponent): 4 Sport (ball – head): 3 Sport (head – ground): 2 Motor vehicle accident: 1
Young Adult Control	10 F / 9 M	20.4 ( $\pm 2.1$ )*	18-26	171.4 ( $\pm 9.7$ )	71.1 ( $\pm 11.1$ )	N/A
Adolescent Concussion	2 F / 17 M	15.1 ( $\pm 1.1$ )	14-17	173.9 ( $\pm 6.5$ )	74.2 ( $\pm 16.9$ )	Sport (head – head): 14 Sport (head – ground): 3 Sport (head – opponent): 2
Adolescent Control	2 F / 17 M	15.6 ( $\pm 1.1$ )	14-17	172.9 ( $\pm 8.1$ )	68.8 ( $\pm 11.1$ )	N/A

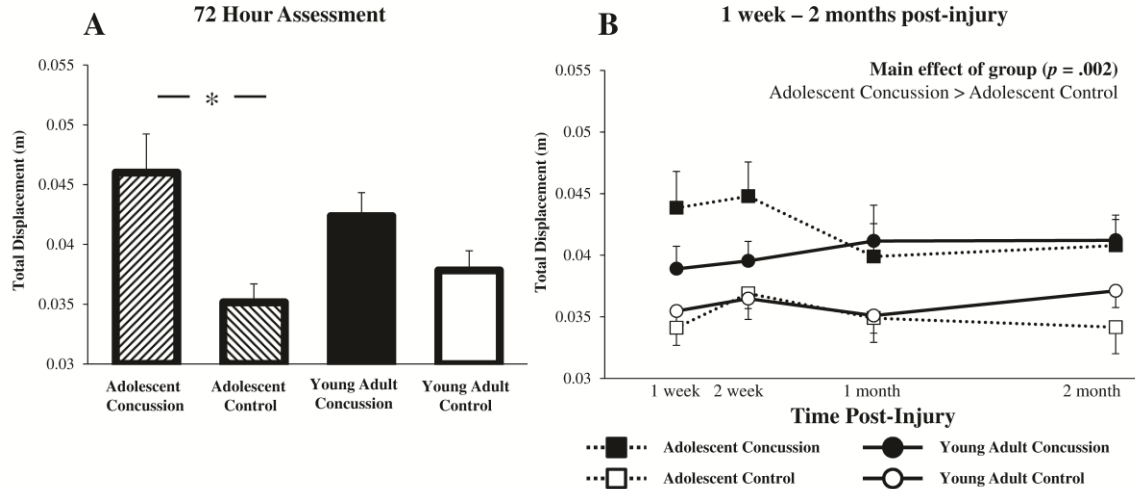
\*: significantly greater than the adolescent concussion and adolescent control group.

Concussion subjects were assessed at: 2 (0.7), 8 (1.8), 17 (3.1), 30 (3.6), and 58 (4.3) days post-injury. Control subjects underwent an initial assessment and then were assessed at 8 (1.7), 16 (3.6), 30 (3.4), and 58 (6.7) days after initial assessment. No subject reported sustaining a concussion during the testing period. No attrition occurred among the 76 subjects in the study.

#### *Center-of-Mass Movement*

The 72 hour post-injury results for total COM medial-lateral displacement indicated a significant main effect of group [ $F(3, 75) = 4.77, p = .004, \eta^2 = .125$ ; Figure 15A]. Follow-up comparisons revealed adolescent concussion subjects walked with significantly greater total COM medial-lateral displacement than adolescent controls ( $p = .005$ ) while no significant difference was observed between young adult groups ( $p = .149$ ). The results across the two months post-injury revealed a significant main effect of group for total COM medial-lateral displacement during dual-task walking [ $F(3, 75) = 5.26, p = .002, \eta_p^2 = .182$ ; Figure 15A/B]. The adolescent concussion group demonstrated significantly more total COM medial-lateral displacement than the adolescent control group throughout the two months of testing ( $p = .001$ ), while the difference between young adult concussion and control groups approached, but did not achieve significance throughout the same time period ( $p = .07$ ). No differences were detected between concussion groups or between control groups.

## DUAL-TASK TOTAL COM MEDIAL-LATERAL DISPLACEMENT



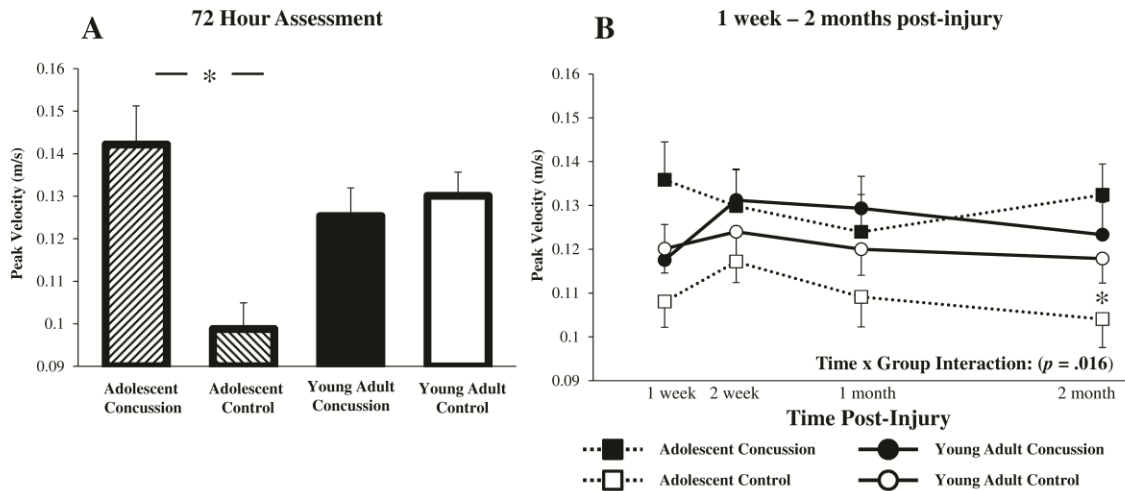
**Figure 15:** Mean  $\pm$  SE total COM medial-lateral displacement for: A) the initial assessment within 72 hours of injury for the four groups of subjects, and B) performance by all four groups examined across two months of post-injury testing.

\* : significant difference between adolescent concussion and control groups.

At 72-hours post-injury, peak COM medial-lateral velocity analysis revealed a main effect of group [ $F(3, 75) = 5.76, p < .001, \eta^2 = .221$ ; Figure 16A]. The adolescent concussion group walked with significantly greater peak COM medial-lateral velocity than adolescent controls ( $p < .001$ ), while young adult concussion and control groups were not significantly different. Analysis for peak COM medial-lateral velocity across the two months of testing revealed a significant time x group interaction [ $F(12, 284) = 2.20, p = .012, \eta_p^2 = .085$ ; Figure 16A/B]. The adolescent concussion group displayed greater peak COM medial-lateral velocity than adolescent controls at the two month testing time point only ( $p = .004$ ). Significant differences were not detected between young adult concussion and control groups, between concussion groups or between control groups.



## DUAL-TASK PEAK COM MEDIAL-LATERAL VELOCITY

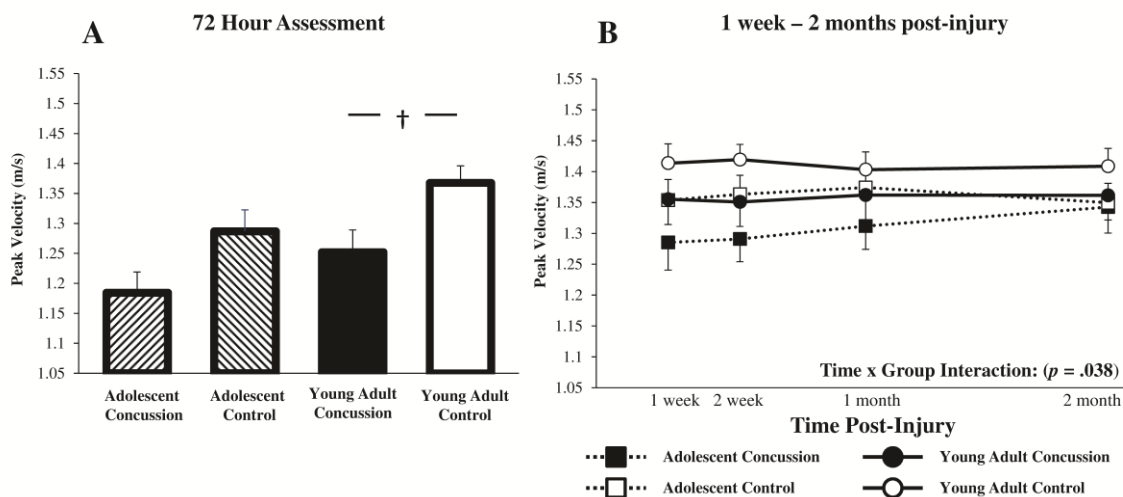


**Figure 16:** Mean  $\pm$  SE peak COM medial-lateral velocity for: A) the initial assessment within 72 hours of injury for the four groups of subjects, and B) performance by all four groups examined across two months of post-injury testing.

\* : significant difference between adolescent concussion and control groups.

Peak COM anterior velocity analysis revealed a main effect of group at 72 hours post-injury [ $F(3, 75) = 8.36, p = .001, \eta^2 = .200$ ; Figure 17A]. The young adult concussion group walked with significantly less peak COM anterior velocity than its corresponding control group ( $p = .01$ ) while the adolescent concussion group did not significantly differ from its corresponding control group ( $p = .03$ ). The results for peak COM anterior velocity across the two months of testing indicated a significant time x group interaction [ $F(12, 284) = 2.05, p = .038, \eta_p^2 = .080$ ; Figure 17A/B]. However, no significant follow-up comparisons were detected between groups or across time.

## DUAL-TASK PEAK COM ANTERIOR VELOCITY



**Figure 17:** Mean  $\pm$  SE peak COM anterior velocity for: A) the initial assessment within 72 hours of injury for the four groups of subjects, and B) performance by all four groups examined across two months of post-injury testing.

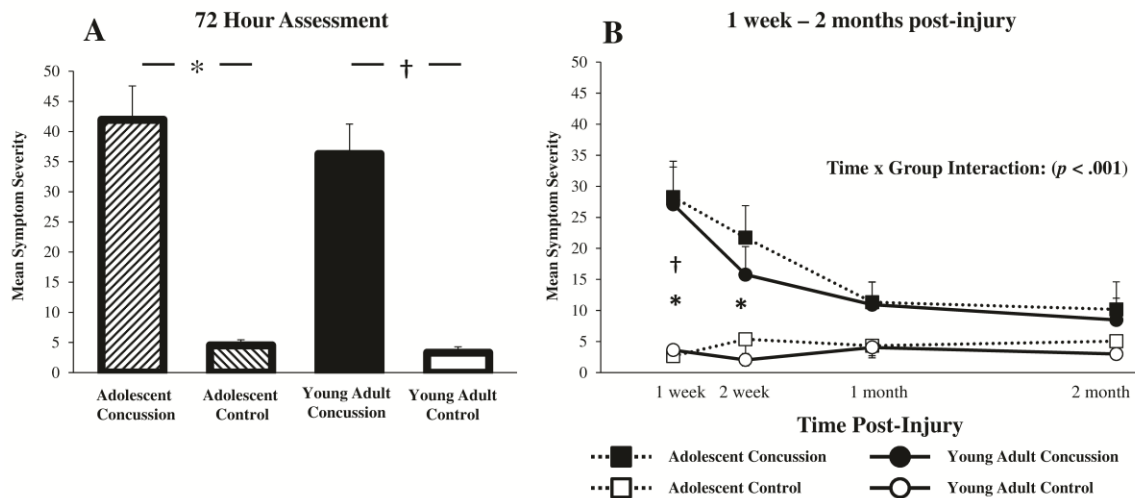
† : significant difference between young adult concussion and control groups.

### *Symptom Severity Inventory*

Within 72 hours of injury, a main effect of group was found for self-reported symptom severity [ $F(3, 75) = 26.11, p < .001, \eta^2 = .521$ ; Figure 18A]. Young adult and adolescent concussion subjects reported significantly more symptoms than their respective controls ( $p < .001$ ). Symptom severity analysis across the two months of testing indicated a significant time x group interaction [ $F(12, 284) = 8.59, p < .001, \eta_p^2 = .266$ ; Figure 18A/B], as the adolescent concussion group reported significantly greater symptom severity than adolescent controls at the one week ( $p < .001$ ) and two week ( $p = .002$ ) time points, but significant differences were no longer observed at the one month or two month time points. The young adult concussion group reported significantly greater symptom severity than the young adult control group at one week post-injury ( $p < .001$ ),

but differences were no longer significant throughout the rest of the testing period. No differences were detected between concussion groups or between control groups.

### SELF-REPORTED SYMPTOM SEVERITY



**Figure 18:** Mean  $\pm$  SE self-reported symptom severity for: A) the initial assessment within 72 hours post-injury and B) performance by all four groups across two months of post-injury testing.

\* : significant difference between adolescent concussion and control groups.

† : significant difference between young adult concussion and control groups.

### Discussion

The study data revealed that initially after injury, and throughout the two month post-injury period, adolescents with concussion displayed greater total COM medial-lateral displacement during dual-task walking compared to their controls than did the young adults with concussion compared to their controls. As no previous work has directly compared age-related gait balance control deficits following concussion, the results suggest that adolescents with concussion may have greater difficulty controlling medial-lateral COM movement during divided attention walking than young adults who

have sustained a concussion, supporting the notion that adolescents may require a more conservative management plan post-concussion (73, 112, 119).

Rather than the younger brain being more “plastic” and thus better able to recover from injury than an adult brain (2), younger individuals who sustain head trauma may actually be more vulnerable to the effects from head injury (2, 119). Previous age group recovery time differences following concussion have been documented through neuropsychological testing outcomes, observing that high school athletes required a longer recovery than college athletes (55). Memory impairments for high school athletes have also been reported to last longer than collegiate athletes post-concussion (35), and adolescents have previously displayed electrophysiological impairments for a longer duration of time than pediatric or young adult age groups following a concussion (4). The current study data revealed that medial-lateral COM motion control during dual-task walking was affected by concussion throughout the two months of testing for adolescents, potentially indicating a decreased ability to control balance while walking (77).

While total COM medial-lateral displacement differences between young adult concussion and control groups did not achieve significance in the current study, previous dual-task gait stability impairments for up to 4 weeks post-injury have been reported in a cohort of collegiate athletes after concussion while subjects walked and completed a mental status examination (128), rather than the continuous auditory Stroop task utilized in the current study. This is an important methodological difference, as recent evidence suggests that cognitive task complexity during dual-task walking differentially affects gait stability following concussion (78). Since the secondary task used in the current

study has been identified as a less complex task than a mental status examination (78), it may not have provided the necessary complexity to detect deficits between healthy and injured young adult groups.

Consistent with previous work, current study data identified that young adults with concussion displayed significantly smaller peak COM anterior velocity compared to control subjects within 72 hours of injury (30). Smaller peak forward velocity may be indicative of a reduction of attentional resources due to concussion, potentially resulting in a reduced ability to control forward momentum in order to accommodate the increased attentional demand imposed by the dual-task condition (30, 69).

Prior work has reported that adolescents with concussion display memory deficit variability during the week following injury, suggesting that recovery may not always occur linearly across time (55). In the current study, adolescents with concussion displayed a significantly greater medial-lateral peak velocity compared to controls within 72 hours post-injury and again two months post-injury. Gait stability regression has been identified in young adults following the return to pre-injury physical activities after concussion (128), supporting the observation of a non-linear recovery phenomenon.

A recent comparison between adolescent and young adult age groups revealed no age-related differences on post-concussion symptom severity scores (93). The current study data indicate that adolescents with concussion had significantly greater symptom severity than matched controls for up to one month post-injury, while young adults with concussion displayed differences from controls only up to two weeks post-injury. This may be explained, in part, by prior work suggesting that a protracted state of physiologic abnormalities that lead to symptom generation following concussion may exist for a

longer duration of time in adolescent-aged individuals than in adults, and that these disturbances may result in a longer time duration required for symptom resolution (104).

#### *Study Limitations*

While each study participant with concussion was diagnosed by a healthcare professional, the management recommendations may have varied between healthcare providers. Further, all adolescents were injured during sport participation, while a majority, but not all of the young adults were injured during sport participation. While the role this plays in the results observed is unknown, a consistent definition of concussion was utilized in the identification of all subjects in this study.

#### Conclusion

By assessing dynamic balance control during dual-task walking, it was observed that adolescents demonstrated greater difficulty controlling their frontal plane COM movement throughout the two months following injury than young adults who completed the same testing protocol. These data support the view that adolescents may be particularly sensitive to the balance control effects of concussion and that this population requires a more conservative post-injury management approach.

## CHAPTER VII

### FINDINGS SUMMARY AND CONCLUSION

#### Findings Summary

This dissertation represents a compilation of studies which are among the first to present data employing a prospective and longitudinal approach to examine recovery from concussion through cognitive and motor assessments in an adolescent population for a time period of up to two months post-injury. The data suggest that adolescents who sustain a concussion may require a longer duration of time than traditionally suggested to fully recover on attention and gait balance control abilities. Furthermore, it appears that the adolescent population may be at particular risk to the sustained effects of a single concussion and should be managed conservatively. The information from this collection of studies may help to identify key factors necessary for the accurate and objective monitoring during recovery, thus assisting in the individualized management plan of those who sustain a concussion.

#### Future Research

The data reported throughout this study have identified that gait balance control is particularly affected by concussion and dual-task assessments may provide a technique to assess such deficits. However, to make these assessments, laboratory-based motion analysis equipment is required. As it is expensive and relies on experienced personnel for its use, widespread clinical use may not be feasible. The development of new assessments which accurately assess dynamic balance control which can also be utilized in the clinical setting may best help to translate these findings to clinical practice. As

recent research has implemented the use of an inertial measurement unit to assess static balance ability (21, 86), the use of such a device may be feasible for the detection of gait imbalance and provide a way for healthcare providers to sensitively track recovery from concussion. Future research should also examine the structural and physiological mechanisms underlying motor function disturbances following injury. Such examinations may be possible through the use of transcranial magnetic stimulation or magnetic resonance imaging technologies.



## APPENDIX A

### ABBREVIATION LIST

ANT: Attention Network Test

ATP: Adenosine Triphosphate

BESS: Balance Error Scoring System

COM: center of mass

COP: center of pressure

DTI: diffusion tensor imaging

MAS: multiple auditory Stroop test

M/L: medial/lateral

mTBI: mild traumatic brain injury

PFC: prefrontal cortex

Q&A: question and answer test

RT: response time

RTA: return to activity

SAS: single auditory Stroop test

SCAT2: standardized concussion assessment tool, version 2

SPSS: Statistical Package for the Social Sciences

TBI: traumatic brain injury

TST: Task Switching Test

## APPENDIX B

### REVIEW OF LITERATURE

#### Introduction

Recently, mild traumatic brain injury (mTBI) has received increased attention, most notably from various media sources which have largely focused on the effects of brain injury during sport participation or military-related activity. Such increased attention has also been apparent in scientific research, as approximately 1500 studies related to the topic of concussion have been published in the past ten years (124). Despite such widespread focus on the short and long term effects of mTBI, much is still unknown. The diagnosis and management of the injury still remains controversial and variable among healthcare professionals (46).

Concussion and mTBI both lack a strict and concise definition, as many different definitions of each exist (44, 73, 87). However, it is generally agreed upon that concussion is a subset of mTBI (73). In 2013, the *Consensus statement on concussion in sport* defined concussion as a brain injury which may either be caused by a direct blow to the head, face, neck, or elsewhere on the body with an impulsive force transmitted to the head, resulting in a graded set of clinical symptoms (112). This definition is consistent with clinical position statements (63) and may best encompass the entity of a concussion. In contrast, mTBI is typically associated with a type of lesion induced by a mechanical force to the brain (87). As a result of these two terms being used interchangeably, communication and comparison of study results may be diminished (87). Thus, throughout this dissertation, the term concussion was used as all subjects included were diagnosed by healthcare providers with concussion rather than mTBI.

It has been estimated that 136,000 concussions occur per academic year in high school athletics alone (58), although this may not represent the total number of injuries that happen due to lack of recognition or underreporting associated with concussion (89, 109). Concussion has been reported to account for approximately 9% of all injuries in high school athletics, representing a large proportion of injuries sustained by this population (58). Incidence rates for high school athletes have steadily increased over the past decade, potentially due to increased awareness about the injury, increased medical personnel on-site for athletic events, or overall increased sport participation (95). As a result of the increased incidence of injury, or increased attention given to the effects of concussion, legislation has been enacted in a majority of the United States at a state level in order to protect youth athletes and increase education and awareness about the injury (157). However, recent evidence has identified that despite the passage of such laws, adolescent athletes may still continue to practice or play while suffering from the known symptoms of a concussion, despite signing a statement during the beginning of the season stating that they would report such symptoms to their coach or medical personnel (141). Thus, more objective and accurate methods of detecting concussion and subsequent recovery may be needed to supplement the standard clinical exam for injury diagnosis and management (141).

Initially, in order to identify the characteristics of a concussion, grading scales were used to provide a means to grade severity, predict duration of recovery, and to prevent catastrophic injury in younger individuals suffering from head trauma. Such scales relied on initial signs and symptoms associated with the injury, but as little scientific evidence has supported them, none were universally accepted and gradually

they have been abandoned (117). Thus, the need exists to better understand how an individual recovers from concussion, what factors affect recovery, and which assessment techniques may provide the best information pertaining to recovery.

### Concussion Biomechanics, Anatomy, and Physiology

Concussion has often been described as a functional disturbance rather than a structural injury (100, 111, 112, 145), however recent reports have identified apparent structural changes occurring after a single concussive event (44, 82, 130, 172) which may require a longer duration of time to heal than clinical testing paradigms are currently equipped to identify (155). The concussive event occurs when force is transmitted to brain tissue following a head impact (18). These forces typically result in a rapid acceleration or deceleration of the brain within the cranium and the mechanical energy transferred to the brain results in damage to neuron structure and function, and is hypothesized to underlie common signs and symptoms associated with the clinical presentation of subjects who have sustained a concussion (104).

The biomechanics related to a concussion are more complex than just the forces, masses, and accelerations of the head of an individual impacting with other objects. Variations in size, strength, equipment, impact direction, and anticipatory muscle contraction, may influence the stress to brain tissue and how an individual will respond to a given impact (18, 120). Linear and rotational forces imparted create different types of disturbances and damages throughout the brain leading to a challenging injury assessment (124). Different research groups have investigated a threshold necessary to impart a concussion, but due to these myriad of factors that modify concussion tolerance,

have yielded inconclusive results thus far (18, 65, 114, 171). While linear and angular acceleration and impact location play a prominent role in the cause of a concussion, intrinsic factors also play a role in how an individual recovers from injury. Factors such as concurrent pathologies, cerebrospinal fluid volume, cerebral blood flow, or sleep abnormalities may influence the injury incidence and subsequent recovery (18).

Leading hypotheses about the pathophysiology of the concussive event state that the mechanical trauma induces shear strain to the skull resulting in axonal membrane deformation and stretching throughout the brain (60, 147). This deformation creates many different disruptions to cell signaling and ion channels throughout the brain and central nervous system. Extracellular potassium levels increase while simultaneously excess amounts of glutamate are released and intracellular calcium accumulates, leading to mitochondrial apoptosis. Each of these separate but simultaneous events may occur within minutes of the concussive event throughout the brain (60, 147). As a result, an energetic crisis occurs due to the decreased ability of the brain to auto regulate blood flow to the (60, 104). The blood supply and consequent glucose needed to supply energy to the ion pumps and glial cells which help to enable the restorative properties to the brain require a large amount of Adenosine Triphosphate (ATP). But, due to the large-scale ionic gradient disruption and inability to deliver ATP to the brain due to cerebral dysautoregulation, the demand for ATP exceeds the ability to supply it. This mismatch of supply and demand is thought to create the symptoms commonly associated with concussion (60, 72, 104).

These post-concussive pathophysiological changes have been reported to increase the brain's vulnerability to a second concussive event, leading to further damage, more

severe or permanent deficits (60, 79, 147, 158, 169). One area of the brain which, when damaged, has been hypothesized to play a role in prevention of re-injury is the motor cortex or the performance of the motor system as a whole (41, 115). Motor system activation and efficiency impairments may reduce the ability to create movement which produces an anticipatory or preventative position prior to an oncoming impact. Recent evidence has suggested that head impact severity decreases as awareness to an oncoming impact increases (120). Following concussion, the motor cortex may have a decreased ability to functionally output information to the muscles responsible for such movements (8), leading to a potential impairment in the ability to volitionally pre-contract neck musculature to prepare for an oncoming impact and subsequent increase in vulnerability to head impacts (120).

Such findings have prompted health care organizations to adopt guidelines which restrict the return to activities in the days following injury (112, 147) and various lawmakers to enact legislation where athletes are not allowed to return to play on the same day as a concussion occurs (157). Such guidelines have been especially prominent within the adolescent population as many treatment guidelines have identified this as a population which requires more conservative treatment due to the critical and rapid brain development that occurs during this time of life (73, 112). Because the young brain is undergoing such developmental changes, injury during this time of life may not only affect the outcome following the injury, but may also deviate from normal development (119, 147). However, despite this potentially increased vulnerability during adolescence, most research up to this point has focused on the recovery patterns of adult individuals, most notably in collegiate and professional athletes.

### Clinical Assessment of Concussion

The clinical evaluation of concussion has changed considerably in recent years as well, however many limitations and controversies still exist (46). Currently, best practice guidelines specify that a clinical medical assessment should include components of a detailed medical history, a detailed neurological exam, cognitive function assessment, and gait or balance function testing (112). Once diagnosed, individuals with a suspected concussion are recommended to be removed from the activity immediately and evaluated further (14). A variety of tools have been made available to help identify the various signs and symptoms associated with a concussion, such as the Standardized Assessment of Concussion (14) and the Standardized Concussion Assessment Tool version 3 (SCAT3) (112). These assessments use techniques such as self-reported symptom severity surveys, immediate and delayed memory, concentration, static balance, and coordination tests (113) to identify dysfunction following an impact to the head.

Following diagnosis, a variety of assessment tools also exist to track recovery to pre-injury levels of function. While many tools have been made available to track and test these functions, none have been universally accepted, leading to a great variety among healthcare professionals regarding what constitutes full recovery from concussion and when an individual should return to pre-injury levels of participation in cognitive and physical activities. However, recent evidence has suggested that using a multi-faceted approach to assess brain function post-concussion may increase sensitivity over any single measurement (136). Therefore, it is recommended that multiple assessments

should be used as a part of the evaluation of recovery (112) and that individuals with concussion should be evaluated and managed on an individual basis (14).

Once a healthcare provider has determined that an individual who has sustained a concussion has recovered and is asymptomatic through the clinical examination and post-injury functional testing, a graded return-to-play progression begins containing 6 distinct steps, each separated by 24 hours (14, 112). This practice specifies that if the patient reports any increase in symptoms during each of the steps, they are placed one step back until their symptoms subside and they begin with the previous step 24 hours later. The 6 steps currently recommended from a variety of statements (14, 73, 112) typically consist of some form of the following:

- 1) No activity
- 2) Light exercise
- 3) Sport-specific exercise without any threat of contact
- 4) Noncontact training involving others or resistance training
- 5) Unrestricted practice
- 6) Return to full activity

Although these steps have been accepted by various health organizations (14, 73, 112), many difficulties with these recommendations have been identified. The average individual is not asymptomatic even when healthy (37), the progression relies on subjective self-reporting and a risk exists for individuals to underreport symptoms (109), evidence has suggested that exercise alone may be enough of a stimulus to elicit symptoms of a concussion (1), and neurological deficits post-concussion often outlast symptom reported resolution (15).



In order to add objective measurements to the evaluation of concussion, two types of tests have been employed in the clinical setting to track recovery: neurocognitive testing and static postural control testing. Cognitive testing was once identified as the cornerstone of concussion management (63) but has more recently been replaced with physical and cognitive rest (112). As cognitive testing represents a clinically feasible and objective test, it is emphasized that such testing techniques are not used as the sole basis for managing concussion, but rather as an aid within the scope of a clinical assessment (112). The most commonly used neurocognitive test is the Immediate Post-Concussion Assessment and Cognitive Test, which has been reported to be in use by over 90% of athletic trainers who utilize a cognitive test as a part of their concussion assessment protocol (118). However, due to such widespread use, there may be a temptation for untrained individuals to use neurocognitive tests as the only marker of recovery and allow individuals to return to pre-injury levels of activity before they have achieved functional or physiological recovery (118).

The clinical assessment of postural control has most frequently included the Balance Error Scoring (BESS) test (86). This assessment identifies instability while standing following injury by instructing the patient to stand in various stances with eyes closed on different types of surfaces, and a clinician rating the number of errors the patient makes in a 20 second trial (11). It has been reported to possess moderate to good reliability (11) and its administration is quick, portable, and cost-efficient. Despite the ease of use, it has been reported to have limitations due to patient learning effects (19) or fatigue effects (160), limiting its potential sensitivity to the effects of concussion. As a result, different research groups have recently sought to increase the reliability of the test by using

accelerometers to objectively detect postural imbalance while completing the various stances of the BESS, but results to this point have yielded mixed findings (21, 57, 86).

Other research groups have sought to quantify the effects of a concussion through the use of various imaging technologies. Reports using magnetic resonance imaging have identified functional abnormalities following concussion when completing spatial navigations tasks (170) and microstructural alterations to white matter tracts (130). Diffusion tensor imaging (DTI) analyses may provide the best information pertaining to white matter integrity and potential damage following injury (146) but concussion management using DTI may not yet be feasible in the clinical setting (164). The third common imaging assessment related to concussion is magnetic resonance spectroscopy, which has identified neurometabolite concentration alterations following concussion for a time period of days (166) to months (75) following injury. While each of these techniques have promise in identification of injury and recovery from injury, their diagnostic use has not yet been validated (14).

#### Attention Following Concussion

It has been documented that following a single sport-related concussion, the incidence of re-injury once the individual has returned to the playing field is three times greater than those who did not sustain an injury (67). Although the specific mechanism for this increased vulnerability to subsequent injury following a first concussion is unknown, animal studies have suggested that following a first injury, a second injurious event may induce an exaggerated injury through the development of sodium channelopathy and thus exacerbated outcomes in second injuries compared to the first (169). Other animal

research has suggested that the effects from TBI are particularly exaggerated in younger brains compared with older brains (135). However, identification of complete recovery continues to be a key element in reducing the risk of subsequent injury, particularly in the sports arena.

Attention has been identified as a key element in the ability of an individual to orient their body in a way prior to an imminent impact and reduce the acceleration and deceleration of the head following the hit (120). If attentional and/or spatial awareness impairments exist, the individual may not be able to react to an oncoming hit and thus be unable to increase the effective mass of their head and neck, leading to greater rotational accelerations and forces transferred to brain tissue (17). These events may help to explain, in part, the vulnerability of an individual to subsequent injury and increasing awareness on the field has been proposed as a potential concussion prevention strategy (117).

Attention has been reported to be comprised as a neural network which corresponds to a specific area during a task and when damaged, may produce a specific attentional deficit (131). These networks have been illustrated to be divided into three separate subsystems which perform different, but inter-related functions: maintenance of vigilance or alertness, focal processing, and sensory event orientation (131). As a result of concussion, separate networks may be affected for a time period of days to a month following injury to the orienting and executive components, respectively (45, 71). Such assessments have been made through the use of the Attention Network Test (ANT), which employs a computerized testing paradigm that measures reaction times among various stimulus-response conditions to evaluate alerting, orienting, and executive

attention in a variety of attentional abnormalities including stroke, schizophrenia, attention-deficit disorder, and brain injury (53).

The competition for attention during walking has also been examined through dual-tasks, where an individual walks while simultaneously performing a cognitive task. Such assessments have also been called divided attention walking tasks, and this terminology refers to the ability to perform greater than a single task at once (168). Difficulties in performance on one or both tasks have been identified through various theories on capacity-sharing, bottleneck, or multiple resource models which each describe different ways that attentional resources are divided during dual-task walking (168). As concussion has been reported to affect attentional capabilities (30, 45, 71), problems in everyday task performance may arise as a result of the injury. Furthermore, concussion has been reported to affect cognitive function and so the addition of a cognitive task during a motor task has been reported to increase sensitivity to the effects of concussion over performance on either task separately (137).

### Balance Following Concussion

Examination of balance control has been documented as a useful tool to objectively assess neurological function following concussion (112). Although the amount of disturbance to balance may depend on injury severity, accurate assessment may provide valuable insights into recovery for clinicians and scientists alike, who seek to improve patient outcomes by successfully managing these subtle disturbances that may outlast the presence of symptoms (50).

Balance has been defined as the body posture dynamics which relate to the prevention of falling (161). In contrast, posture has been described as the orientation of the body in relation to the vector of gravity (161). Clinical assessment of postural control may include a type various standing positions and the evaluation of success or failure in these positions (68, 112). In contrast, balance control may be best monitored through the observation of walking performance, with such measurements as gait velocity and center of mass (COM) sway during walking (165) which have been reported to yield information related whole-body COM control, and commonly been reported as a method to effectively detect imbalance in various populations (6, 28, 33, 70, 129).

In order to maintain balance, one must rapidly integrate incoming somatosensory, visual, and vestibular information and use this information to direct voluntary muscle contractions to generate movement (68). Thus, testing balance control may provide a way to study the interactions of systems commonly affected by concussion (16). Furthermore, the evaluation of dynamic movement is important as it reflects the complexities of navigating everyday life situations (6).

As previously discussed, the sensitivity of a cognitive assessment to the effects of concussion appears to be mitigated by learning effects and potentially reflect the ability to learn more than actual recovery from injury. As both cognitive and motor systems appear to be affected following head trauma, a way to monitor both systems, independently and when performed in conjunction is through the use of a dual-task. This assessment typically involves a motor task simultaneously conducted with a cognitive task. Such experiments have been conducted across a variety of clinical conditions including aging (151), Alzheimer's disease (25), amputees (59), stroke (168), and

Parkinson's disease (168). Dual-tasks necessitate proper allocation of attentional resources, thus challenging the brain to effectively execute both tasks (168). However, if the brain is injured, it may not possess the ability to appropriately allocate resources, and deficits will most likely be seen in cognitive or motor domains, or in a combination of both (148, 168). Recently, it has been concluded that dual-task walking measurements may represent biomechanical markers which are helpful in concussion management (92) and may help to refine concussion assessment to identify the processes affected by the concussion which may require further time to heal (137).

While reports have identified that postural deficits during standing last only for a period of 3-5 days following mTBI (16), dual-task methodologies in assessing dynamic balance during gait have shown deficits which last much longer, even up to one month following injury (127). Parker and colleagues (2007) reported that individuals who had suffered mTBI adopt a more conservative gait strategy, indicated by a slower walking speed and a decreased center of mass – center of pressure (COM-COP) distance than matched control subjects when walking and completing a secondary cognitive task, throughout a four week time period after injury (128). Furthermore, they also reported that while in the dual-task condition, individuals with concussion demonstrated more side to side sway than controls, while not significantly differing than controls in a single task condition. The destabilizing effect the secondary task had on the maintenance of balance following mTBI for a prolonged duration may indicate that dual-tasks may be sensitive to the effects of concussion.

Similar work focused on the contribution of attention to balance control during walking concluded that concussed individuals tend to display more frontal plane range of

motion when walking and completing a Stroop task up to a week following injury (30). This finding demonstrates attention prioritization following mTBI and that tradeoffs in performance may be apparent. Thus, if the brain has been made vulnerable following concussion, decrements may be displayed in balance control for up to a month following injury.

A potential reason balance control is well assessed during a dual-task walking paradigm is due to the contribution of frontal lobe structures to successfully complete both tasks simultaneously. These structures contribute to the planning of purposeful behavior and external stimuli synthesis in order to produce an action (94, 99, 153). Frontal lobe deficits have been shown to be sensitive markers of recovery from TBI, both severe (96) and mild (71, 76). Specifically, the anterior cingulate gyrus and prefrontal cortex have been associated as areas well documented to be activated when performing dual-tasks (168), during attention competition or conflict resolution (51) and affected by brain injury (71).

Reports utilizing dual-tasks have identified that following concussion, the use of simultaneous cognitive and motor tasks may increase the ability to detect deficits for a longer duration of time than isolated cognitive or motor assessment techniques (92, 143). As micro-lesions in the sub-cortical regions of the brain may lead to executive control and/or gait impairments (148), balance control during divided attention walking is an assessment technique which may best represent real-life activities and provide accurate monitoring in the assessment of return to pre-injury health.

## Conclusions

While many studies have investigated the neuropsychological and static balance effects following concussion, few longitudinal and prospective investigations into dynamic motor and cognitive function currently exist, particularly in the adolescent population. Thus, in order to identify accurate ways to sensitively track and identify dysfunction following concussion, it is necessary to study how those who sustain a concussion are affected initially following injury and how they subsequently recover over a duration of two months following injury.



## APPENDIX C

### INFORMED CONSENT FORM:

#### PARENTAL CONSENT FOR CHILD PARTICIPATION

#### **CONSENT FORM (Children 17 years of age or younger)**

Your child is invited to participate in a research study conducted by Drs. Li-Shan Chou, Michael Koester, and Louis Osternig, of the University of Oregon (UO) Department of Human Physiology and the Slocum Center for Orthopedics and Sports Medicine. **This research project is funded in part by the Department of Defense.** We hope to gain a better understanding of how concussion affects attention, concentration and walking. Your child is eligible for being a research participant as he either recently sustained a concussion (concussion subject) or matches the profile of a concussion subject (control subject). The results may provide better information for future identification and management of concussions.

**Your child will be excluded from participating in this research study if any of the following criteria applies.**

- i. A concussion within a year prior to testing.**
- ii. Lower extremity deficiencies that might hinder normal gait.**
- iii. A history of cognitive deficiencies, such as memory loss or difficulty concentrating.**
- iv. A history of two or more concussions prior to one year of testing.**
- v. Loss of consciousness lasting more than one minute.**
- vi. A history of attention-deficit hyperactivity disorder.**

If you give permission, your child will be tested in five separate sessions over the next 2 months in the Motion Analysis Laboratory at the University of Oregon.

The first test in the Motion Analysis Laboratory will include unobstructed level walking and stepping over obstacles of four various heights. Both reflective markers and surface electrodes will be placed on your child's skin at selected bony landmarks and muscle surfaces to record the motion of each individual body segment. Your child's body movement, (indicated by motion of reflective markers) during walking and obstacle crossing, will be recorded by our optoelectronic cameras (or by video cameras, upon your approval) for further analysis. Your child will be asked to wear a pair of paper physical therapy shorts and sleeveless shirt (tank top) during testing. It will take approximately 2 hours to perform this test.

**RISKS AND DISCOMFORTS:** We expect that there will be no more risk for your child during these tests than there normally is for your child when outside of the laboratory. However, your child may feel fatigue during or after the testing. Our staff member will check with your child frequently and provide any required assistance. Your child will be given frequent breaks as requested. There is also the possibility of discomfort involved in removing adhesive tape (used for marker placement) from skin at the end of the test.

Following Gait Analysis, Immediate Post Concussion Assessment and Cognitive Testing (ImPACT) and the Attention Network and Task Switching Tests (ANT-TS) will be administered. ImPACT is a computerized test utilized in many professional, collegiate, and high school sports programs in the United States to assess the effects of concussion. The ANT-TS is also a computerized exam that has been used at the University of Oregon to assess the effects of concussions. These tests track information such as memory, reaction time, attention and concentration. They are not IQ tests. Your child may have already taken tests like these at his/her high school prior to or during the academic year. The ImPACT and the ANT-TS can be used to help determine the severity of the injury and provide information about the recovery. Each test will take about 20-30 minutes to complete.

**RISKS AND DISCOMFORTS:** We expect that taking these tests will pose no risk greater than taking a classroom examination or video game requiring concentration for a period of time similar to complete the tests. However, if your child experiences fatigue during or after the tests, assistance will be provided.

Your child's participation is voluntary and your decision whether to permit participation in the study will not affect your child's relationship with his/her high school, the UO Department of Human Physiology or the Slocum Center for Orthopedics and Sports Medicine. You and your child do not waive any liability rights for personal injury by signing this form. If you have any questions about your child's rights as a research subject, you can contact the Research Compliance Services, 5237 University of Oregon, Eugene, OR 97403, (541) 346-2510, [ResearchCompliance@uoregon.edu](mailto:ResearchCompliance@uoregon.edu). This office oversees the review of the research to protect your rights and is not involved with this study.

If you give permission for your child to participate in the study, you agree to allow the researchers to review existing ImPACT and ANT-TS tests that his/her high school has previously administered for comparison purposes. In order for your child to participate in this study it is necessary for you to authorize release of specific health information related to the concussion your child has sustained. This will require your signature on the attached Authorization Form for Research Disclosure of Personal Health Information. Any information that is obtained in connection with this study and that can be identified with your child will remain confidential and will not be shared with anyone outside of the study without your permission. Subject identities will be kept confidential by coding the data as to study, subject pseudonyms, and collection date. The code list will be kept separate and secure from the actual data files.

If you give permission for your child to participate in this study and your child agrees, your child is free to withdraw your consent and discontinue participation at any time without penalty. A total of 5 testing sessions over a period of 60 days are required for your child to complete participation in this study. Your child will receive \$40 for completion of each testing session. **If your child withdraws his/her participation prior to the completion of a testing session, no payment will be made.**

If you have any questions, please feel free to contact Dr. Li-Shan Chou, (541) 346-3391, Department of Human Physiology, 112C Esslinger Hall, University of Oregon, Eugene OR, 97403-1240. You will be given a copy of this form to keep. Your signature indicates that you have read and understand the information provided above, that you willingly agree to permit your child participate, that you may withdraw your consent at any time and discontinue participation without penalty, that you will receive a copy of this form, and that you are not waiving any legal claims, rights or remedies.

I give permission for my child to participate in this study

\_\_\_\_\_  
Printed name of research participant's  
Parent/Legal Guardian

\_\_\_\_\_  
Date

\_\_\_\_\_  
Signature of research participant's  
Parent/Legal Guardian

\_\_\_\_\_  
Printed name of student research participant

## APPENDIX D

### INFORMED CONSENT FORM:

#### CHILD PARTICIPANT CONSENT

### CONSENT FORM (Children 17 years of age or younger)

You are invited to participate in a research study conducted by Drs. Li-Shan Chou, Michael Koester, and Louis Osternig, of the University of Oregon (UO) Department of Human Physiology and the Slocum Center for Orthopedics and Sports Medicine. **This research project is funded in part by the Department of Defense.** We hope to gain a better understanding of how concussion affects attention, concentration and walking. You are eligible for being a research participant as you either recently sustained a concussion (concussion subject) or you match the profile of a concussion subject (control subject). The results may provide better information for future identification and management of concussions.

**You will be excluded from participating in this research study if any of the following criteria applies.**

- i. A concussion within a year prior to testing.**
- ii. Lower extremity deficiencies that might hinder normal gait.**
- iii. A history of cognitive deficiencies, such as memory loss or difficulty concentrating.**
- iv. A history of two or more concussions prior to one year of testing.**
- v. Loss of consciousness lasting more than one minute.**
- vi. A history of attention-deficit hyperactivity disorder.**

If you give permission, you will be tested in five separate sessions over the next 2 months in the Motion Analysis Laboratory at the University of Oregon.

The first test in the Motion Analysis Laboratory will include unobstructed level walking and stepping over obstacles of four various heights. Both reflective markers and surface electrodes will be placed on your skin at selected bony landmarks and muscle surfaces to record the motion of each individual body segment. Your body movement, (indicated by motion of reflective markers) during walking and obstacle crossing, will be recorded by our optoelectronic cameras (or by video cameras, upon your approval) for further analysis. You will be asked to wear a pair of paper physical therapy shorts and a sleeveless shirt (tank top) during testing. It will take approximately 2 hours to perform this test.

**RISKS AND DISCOMFORTS:** We expect that there will be no more risk for you during these tests than there normally is for you when outside of the laboratory. However, you may feel fatigue during or after the testing. Our staff member will check with you frequently and provide any required assistance. You will be given frequent breaks as requested. There is also the possibility of discomfort involved in removing adhesive tape (used for marker placement) from skin at the end of the test.

Following Gait Analysis, Immediate Post Concussion Assessment and Cognitive Testing (ImPACT) and the Attention Network and Task Switching Tests (ANT-TS) will be administered. ImPACT is a computerized test utilized in many professional, collegiate, and high school sports programs in the United States to assess the effects of concussion. The ANT-TS is also a computerized exam that has been used at the University of Oregon to assess the effects of concussions. These tests track information such as memory, reaction time, attention and concentration. They are not IQ tests. You may have already taken tests like these at your high school prior to or during the academic year. The ImPACT and the ANT-TS can be used to help determine the severity of the injury and provide information about the recovery. Each test will take about 20-30 minutes to complete.

**RISKS AND DISCOMFORTS:** We expect that taking these tests will pose no risk greater than taking a classroom examination or video game requiring concentration for a period of time similar to complete the tests. However, if you experience fatigue during or after the tests, assistance will be provided.

Your participation is voluntary and your decision whether to permit participation in the study will not affect your relationship with his/her high school, the UO Department of Human Physiology or the Slocum Center for Orthopedics and Sports Medicine. You do not waive any liability rights for personal injury by signing this form. If you have any questions about your rights as a research subject, you can contact the Research Compliance Services, 5237 University of Oregon, Eugene, OR 97403, (541) 346-2510, [ResearchCompliance@uoregon.edu](mailto:ResearchCompliance@uoregon.edu). This office oversees the review of the research to protect your rights and is not involved with this study.

If you give permission to participate in the study, you agree to allow the researchers to review existing ImPACT and ANT-TS tests that your high school has previously administered for comparison purposes. In order for you to participate in this study it is necessary for you to authorize release of specific health information related to the concussion your child has sustained. This will require your signature on the attached Authorization Form for Research Disclosure of Personal Health Information. Any information that is obtained in connection with this study and that can be identified with you will remain confidential and will not be shared with anyone outside of the study without your permission. Subject identities will be kept confidential by coding the data as to study, subject pseudonyms, and collection date. The code list will be kept separate and secure from the actual data files.

If you give permission to participate in this study and you agree, you are free to withdraw your consent and discontinue participation at any time without penalty. A total of 5 testing sessions over a period of 60 days are required for you to complete participation in this study. You will receive \$40 for completion of each testing session. **If you withdraw your participation prior to the completion of a testing session, no payment will be made.**

If you have any questions, please feel free to contact Dr. Li-Shan Chou, (541) 346-3391, Department of Human Physiology, 112C Esslinger Hall, University of Oregon, Eugene OR, 97403-1240. You will be given a copy of this form to keep. Your signature indicates that you have read and understand the information provided above, that you willingly agree to participate, that you may withdraw your consent at any time and discontinue participation without penalty, that you will receive a copy of this form, and that you are not waiving any legal claims, rights or remedies.

I agree to participate in this study

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Printed name of research participant

\_\_\_\_\_  
Date

\_\_\_\_\_  
Printed name of research participant

## APPENDIX E

### INFORMED CONSENT FORM:

#### COLLEGE STUDENT PARTICIPANT CONSENT

#### **CONSENT FORM (College Students)**

You are invited to participate in a research study conducted by Drs. Li-Shan Chou, Michael Koester, and Louis Osternig, of the University of Oregon (UO) Department of Human Physiology and the Slocum Center for Orthopedics and Sports Medicine. **This research project is funded in part by the Department of Defense.** We hope to gain a better understanding of how concussion affects attention, concentration and walking. You are eligible for being a research participant as you either recently sustained a concussion (concussion subject) or you match the profile of a concussion subject (control subject). The results may provide better information for future identification and management of concussions.

**You will be excluded from participating in this research study if any of the following criteria applies.**

- i. A concussion within a year prior to testing.**
- ii. Lower extremity deficiencies that might hinder normal gait.**
- iii. A history of cognitive deficiencies, such as memory loss or difficulty concentrating.**
- iv. A history of two or more concussions prior to one year of testing.**
- v. Loss of consciousness lasting more than one minute.**
- vi. A history of attention-deficit hyperactivity disorder.**

If you give permission, you will be tested in five separate sessions over the next 2 months in the Motion Analysis Laboratory at the University of Oregon.

The first test in the Motion Analysis Laboratory will include unobstructed level walking and stepping over obstacles of four various heights. Both reflective markers and surface electrodes will be placed on your skin at selected bony landmarks and muscle surfaces to record the motion of each individual body segment. Your body movement, (indicated by motion of reflective markers) during walking and obstacle crossing, will be recorded by our optoelectronic cameras (or by video cameras, upon your approval) for further analysis. You will be asked to wear a pair of paper physical therapy shorts and a sleeveless shirt (tank top) during testing. It will take approximately 2 hours to perform this test.

**RISKS AND DISCOMFORTS:** We expect that there will be no more risk for you during these tests than there normally is for you when outside of the laboratory. However, you may feel fatigue during or after the testing. Our staff member will check with you frequently and provide any required assistance. You will be given frequent breaks as requested. There is also the possibility of discomfort involved in removing adhesive tape (used for marker placement) from skin at the end of the test.

Following Gait Analysis, Immediate Post Concussion Assessment and Cognitive Testing (ImPACT) and the Attention Network and Task Switching Tests (ANT-TS) will be administered. ImPACT is a computerized test utilized in many professional, collegiate, and high school sports programs in the United States to assess the effects of concussion. The ANT-TS is also a computerized exam that has been used at the University of Oregon to assess the effects of concussions. These tests track information such as memory, reaction time, attention and concentration. They are not IQ tests. You may have already taken tests like these at your high school prior to or during the academic year. The ImPACT and the ANT-TS can be used to help determine the severity of the injury and provide information about the recovery. Each test will take about 20-30 minutes to complete.

**RISKS AND DISCOMFORTS:** We expect that taking these tests will pose no risk greater than taking a classroom examination or video game requiring concentration for a period of time similar to complete the tests. However, if you experience fatigue during or after the tests, assistance will be provided.

Your participation is voluntary and your decision whether to permit participation in the study will not affect your relationship with his/her high school, the UO Department of Human Physiology or the Slocum Center for Orthopedics and Sports Medicine. You do not waive any liability rights for personal injury by signing this form. If you have any questions about your rights as a research subject, you can contact the Research Compliance Services, 5237 University of Oregon, Eugene, OR 97403, (541) 346-2510, [ResearchCompliance@uoregon.edu](mailto:ResearchCompliance@uoregon.edu). This office oversees the review of the research to protect your rights and is not involved with this study.

If you give permission to participate in the study, you agree to allow the researchers to review existing ImPACT and ANT-TS tests that your high school has previously administered for comparison purposes. In order for you to participate in this study it is necessary for you to authorize release of specific health information related to the concussion your child has sustained. This will require your signature on the attached Authorization Form for Research Disclosure of Personal Health Information. Any information that is obtained in connection with this study and that can be identified with you will remain confidential and will not be shared with anyone outside of the study without your permission. Subject identities will be kept confidential by coding the data as to study, subject pseudonyms, and collection date. The code list will be kept separate and secure from the actual data files.



If you give permission to participate in this study and you agree, you are free to withdraw your consent and discontinue participation at any time without penalty. A total of 5 testing sessions over a period of 60 days are required for you to complete participation in this study. You will receive \$40 for completion of each testing session. **If you withdraw your participation prior to the completion of a testing session, no payment will be made.**

If you have any questions, please feel free to contact Dr. Li-Shan Chou, (541) 346-3391, Department of Human Physiology, 112C Esslinger Hall, University of Oregon, Eugene OR, 97403-1240. You will be given a copy of this form to keep. Your signature indicates that you have read and understand the information provided above, that you willingly agree to participate, that you may withdraw your consent at any time and discontinue participation without penalty, that you will receive a copy of this form, and that you are not waiving any legal claims, rights or remedies.

I agree to participate in this study

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Printed name of research participant

\_\_\_\_\_  
Date

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Printed name of research participant

## APPENDIX F

### INFORMED CONSENT FORM:

#### HIGH SCHOOL (OVER 18) PARTICIPANT CONSENT

##### CONSENT FORM

##### **(High school subjects 18 years of age or older)**

You are invited to participate in a research study conducted by Drs. Li-Shan Chou, Michael Koester, and Louis Osternig, of the University of Oregon (UO) Department of Human Physiology and the Slocum Center for Orthopedics and Sports Medicine. **This research project is funded in part by the Department of Defense.** We hope to gain a better understanding of how concussion affects attention, concentration and walking. You are eligible for being a research participant as you either recently sustained a concussion (concussion subject) or you match the profile of a concussion subject (control subject). The results may provide better information for future identification and management of concussions.

**You will be excluded from participating in this research study if any of the following criteria applies.**

- i. A concussion within a year prior to testing.**
- ii. Lower extremity deficiencies that might hinder normal gait.**
- iii. A history of cognitive deficiencies, such as memory loss or difficulty concentrating.**
- iv. A history of two or more concussions prior to one year of testing.**
- v. Loss of consciousness lasting more than one minute.**
- vi. A history of attention-deficit hyperactivity disorder.**

If you give permission, you will be tested in five separate sessions over the next 2 months in the Motion Analysis Laboratory at the University of Oregon.

The first test in the Motion Analysis Laboratory will include unobstructed level walking and stepping over obstacles of four various heights. Both reflective markers and surface electrodes will be placed on your skin at selected bony landmarks and muscle surfaces to record the motion of each individual body segment. Your body movement, (indicated by motion of reflective markers) during walking and obstacle crossing, will be recorded by our optoelectronic cameras (or by video cameras, upon your approval) for further analysis. You will be asked to wear a pair of paper physical therapy shorts and a sleeveless shirt (tank top) during testing. It will take approximately 2 hours to perform this test.

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**RISKS AND DISCOMFORTS:** We expect that taking these tests will pose no risk greater than taking a classroom examination or video game requiring concentration for a period of time similar to complete the tests. However, if you experience fatigue during or after the tests, assistance will be provided.

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If you give permission to participate in the study, you agree to allow the researchers to review existing ImPACT and ANT-TS tests that your high school has previously administered for comparison purposes. In order for you to participate in this study it is necessary for you to authorize release of specific health information related to the concussion your child has sustained. This will require your signature on the attached Authorization Form for Research Disclosure of Personal Health Information. Any information that is obtained in connection with this study and that can be identified with you will remain confidential and will not be shared with anyone outside of the study without your permission. Subject identities will be kept confidential by coding the data as to study, subject pseudonyms, and collection date. The code list will be kept separate and secure from the actual data files.

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If you have any questions, please feel free to contact Dr. Li-Shan Chou, (541) 346-3391, Department of Human Physiology, 112C Esslinger Hall, University of Oregon, Eugene OR, 97403-1240. You will be given a copy of this form to keep. Your signature indicates that you have read and understand the information provided above, that you willingly agree to participate, that you may withdraw your consent at any time and discontinue participation without penalty, that you will receive a copy of this form, and that you are not waiving any legal claims, rights or remedies.

I agree to participate in this study

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Printed name of research participant

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Date

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Printed name of research participant

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