ATTENTION AND GAIT PERFORMANCE FOLLOWING A CONCUSSION

by

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A DISSERTATION

Presented to the Department of Human Physiology
and the Graduate School of the University of Oregon
in partial fulfillment of the requirements
for the degree of
Doctor of Philosophy

June 2008

University of Oregon Graduate School

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Title:

"Attention and Gait Performance Following a Concussion"

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An Abstract of the Dissertation of

Robert David Catena for the degree of Doctor of Philosophy

in the Department of Human Physiology to be taken June 2008

Title: ATTENTION AND GAIT PERFORMANCE FOLLOWING A CONCUSSION

Approved: ______________________________

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Currently the information on attention-balance control interactions following concussion is incomplete and not given particular consideration during clinical examinations of concussion. The purposes of this dissertation were to (1) test different gait paradigms for their sensitivity of identifying concussion symptoms and to (2) test how individual components of attention interact with gait performance. The long-term goal of this study is to establish more functional and succinct protocols for return-to-play decisions.

Grade II (AAN guidelines) concussed individuals were recruited to participate in testing at 2, 6, 14, and 28 days post-injury. Gait and components of attention were analyzed during each session through a number of different paradigms. Control subjects were matched by stature, age, and athletic participation.

The results indicate that the dynamic balance deficits following a concussion are immediately identified with an attention dividing gait task. Obstacle crossing identified more conservative adaptations 2 weeks after injury. A task combining the two did not clearly identify concussion deficits. Two components of attention showed promise as interacting with gait to cause balance deficits. The spatial orientation component showed an interaction with obstacle avoidance indicating that the same concussed individuals that had poor spatial orientation of attention also came closer to hitting the obstacle during crossings. An analysis of divided attention showed that concussed individuals performing poorly in one task also performed poorly in the other during a dual-task paradigm, but during any one particular trial there was a trade-off between task performances, which was not present in control individuals.

The findings of this dissertation point to the use of a divided attention task to distinguish concussed individuals from healthy individuals immediately after a possible injurious event. How several different components of attention interact with gait performance is identified. Finally, if a concussion has occurred, an obstacle crossing task might be suitable for a long-term analysis of full recovery of balance control. Ultimately, it is my hope that the information provided here will lead to functionally relevant and clinically executable tests of concussed individuals before they are placed in harm's way due purely to an incomplete diagnosis of their injuries.

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PUBLICATIONS:

Siu KC, Catena RD, Chou LS, van Donkelaar P, Woollacott MH. Effects of secondary task on obstacle avoidance in healthy young adults. Experimental Brain Research in press.

Catena RD, van Donkelaar P, Chou LS. Altered balance control after concussion is better detected by attention tests during gait. Gait & Posture 2007;25:406-11.

Catena RD, van Donkelaar P, Chou L-S. Cognitive task effects on gait stability following concussion. Experimental Brain Research 2007;176:23-31.

Catena RD. Secondary task effects on gait stability in concussed college subjects, Master's Thesis, University of Oregon, Eugene, Oregon. 2005.

ACKNOWLEDGMENTS

Love, friendship, encouragement and five years of long work days and managing household duties is what my wife provided while I was left to focus on my studies. For this, I must gratefully acknowledge Laurel and all her other contributions towards my degree. Family and friends also played a tremendous supporting role during an arduous five years. And of course, none of it would be possible or even matter without God's guidance.

I also appreciated the experience, guidance, and provisions that my advisory committee provided. At the forefront of that support was Dr. Chou, who was courageous enough to take on as an advisee five years ago and patient enough to stick with me after each year. To the other members of my committee, thank you for putting up with the constant questions and providing complete, concise and relatively instantaneous answers.

To my colleagues/friends in the lab (Shing-Jye Chen, Heng-Ju Lee, Tonya Parker, Cherise Robinson, David Mandeville, Sarah Everman, Jung-Hung Chien, Joseph Siu, Jeff Beavers, Virginia Klausmeier, Vipul Lugade, Sue Ewers, Chu-Jui Chen, Jacqueline Poston, Erik Noren, Masahiro Fujimoto), these past five years have been unforgettable, and I will certainly cherish our friendships in the years to come.

This investigation has been supported in part by the American Society of Biomechanics Grant in Aid and grants to Dr. Li-Shan Chou at the University of Oregon from the Center for Disease Control and Prevention (R49/CCR021735 and CCR023203). Support from these agencies has been invaluable in pursuit of my research goals.

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

CHAPTER I

GENERAL INTRODUCTION

Background and Significance

There are 1.4 million new cases of traumatic brain injury (TBI) each year [1]. Of those, close to 230,000 are hospitalizations with a surviving individual [2]. The majority consists of those that are casualties, those that go undiagnosed, and those that are diagnosed but not treated. Approximately 75% of TBIs that occur each year are concussions or other forms of mild TBI [3].

Two common symptoms of a concussion are attention deficits and movement (i.e. strength, coordination and balance) disabilities [4]. These deficits of concussion are particularly important because they can possibly lead to subsequent concussions, as has been eluded to with epidemiological evidence [5]. The effects of a second concussion within years of a previous concussion can cause exacerbated neurological and cognitive deficits [6]. However, repeated concussions occurring within a short period of time (i.e., hours, days, or weeks) can be catastrophic or fatal [6]. The areas of deficits mentioned above are broad areas of human neurological functioning. If, however, we can pinpoint key aspects brought on by the concussion and use these tests clinically, then we can begin the process of accurately identifying and consistently treating the symptoms of the concussion before the lead to subsequent concussions and more permanent damage.

Goals and Specific Aims

The long-term goals of this research are to;

1. discover which components of dynamic balance control and attention interact following concussion to determine a more effective method of identifying lasting effects,
2. track the interaction of balance control during gait and attention, and its possible recovery following a concussion,
3. form recommendations for the clinical examination of patients suffering from concussion.

More specifically, it is hoped that the outcomes of this work will ultimately result in a clinical examination protocol to test the resolution of all (not just particular) symptoms of a concussion that contribute to subsequent concussions and further, more severe, brain injury. While neuropsychological and physiological examinations are important for analyzing many of the important cognitive and physiological functions for daily living, these symptoms can only contribute so much to further injuries. Along with decreased tolerance thresholds to further concussions, one must also consider subsequent concussion susceptibility as a function of the physical predicaments that lead to biomechanical blows to the head. Attention and balance deficits are two important factors that put one in a biomechanically unsafe situation. Functional assessments of attention and dynamic balance control following a concussion seem likely to reduce the occurrence of re-injury and permanent brain damage. Therefore, the focus of this proposed work was on whole body dynamic balance control and its interaction with attention following concussion.

Within the context of this overall objective, four specific aims were proposed in this project:

1. Previous literature proclaiming a protocol's ability to pinpoint the effects of concussion on dynamic balance control have either forgone comparisons between multiple experimental paradigms or limited examinations to a single, sometimes arbitrary testing time post-injury. This experiment will be a validating comparison between paradigms described in current literature as to their ability to distinguish balance control effects of a concussion. It will track recovery using a longitudinal analysis. An attention dividing cognitive task is hypothesized as superior in detecting dynamic balance control abnormalities in concussed individuals throughout the longitudinal analysis.
2. Simultaneous performance of previously used paradigms involving increased motor demand as well as increased attentional demand following concussion has not been explored in the literature. Such information would help quantify and describe the challenge concussed individuals experience during highly demanding real-world tasks. The purpose of this experiment will be to examine whether increased motor and attentional demand accumulate into even poorer gait performance following a concussion, or if there is a ceiling effect where concussed individuals don not experience further balance control deficits. I

suspect that a ceiling effect exists in motor imbalance at the sacrifice of cognitive secondary task performance.

3. Inability to appropriately orient attention and changes in obstacle-crossing strategies are commonly described in concussion literature. It seems likely that obstacle-crossing performance would rely on an ability to appropriately orient attention within space. In fact, literature describes obstacle avoidance during reaching tasks as processed in the same areas as spatial orientation of attention.[7-10]. This experiment will examine the correlation between spatial orientation of attention and obstacle avoidance during gait. It will also attempt to uncover the extent to which any correlations in such tasks are managed by concussed individuals during their recovery. I hypothesize a correlation between spatial orientation and a conservative obstacle avoidance strategy. Concussed participants that are suffering from spatial orientation deficits are expected to be in danger of obstacle contacts.
4. Executive function's conflict resolution is a specific component of attention that remains impaired up to a month post-concussion. The purpose of this experiment is to analyze the effects of conflict resolution on dynamic balance control after a concussion, and the effects of gait on conflict resolution. At the same time, the division of attention in a dual-task paradigm will analyze attention capacity effects. I expect a conflict resolution task to result in only minor gait stability changes; however, an analysis of conflict resolution is expected to indicate even poorer performance when conflicting stimuli are presented to mTBI subjects.

Summary

This study was designed with two primary components. First, there were two experimental protocols devoted to examining attention and balance control during gait for the purpose of finding a protocol sensitive to the effects of concussion. These two experiments compare a dual-task gait protocol against obstacle-crossing tasks and level walking tasks that have been used in the past to examine the dynamic balance control effects of concussion. Whole body balance control data is collected from two groups: healthy young adults and recently concussed young adults (30 subjects in each). Secondly, there were two experimental protocols devoted to examining how dynamic motor performance is related to several specific components of attention that are altered due to a concussion: spatial orientation of attention, conflict resolution and attention division. The knowledge gained from this proposed research will enhance our understanding of the biomechanical challenges imposed on maintenance of dynamic balance control of the whole body and how those challenges might interact with attention in both healthy and concussed young adults. This will further allow us to better identify a sensitive measure for testing concussed individuals before they return to normal activities. Utilizing the information provided by this study, the hope is that future researchers will examine how to apply it to clinical testing so that subsequent injuries may be reduced in the general population.

Flow of the Dissertation

This dissertation is structured in a journal format. Following the general review of literature (Chapter II), chapters III through VI represent individual manuscripts that are in various stages of submission/revision to peer-reviewed scientific journals.

Chapter III describes the sensitivity of longitudinally analyzing balance control during locomotion with level walking, obstacle crossing and dual-task walking of individuals with and without a concussion. The following chapter (IV) details balance control of concussed individuals during attention divided obstacle crossing. Finally, the longitudinal sensitivity of each task is compared in chapter III and IV.

The fifth chapter investigates the relationship between spatial orientation of attention and obstacle crossing following concussion. In this chapter performance during the spatial orientation task presented via a simple computer test is compared to foot obstacle avoidance during gait.

In the sixth chapter the relationship between conflict resolution and dynamic balance control is examined and the division of attention between two simultaneously performed tasks is examined. An auditory Stroop task is presented during level walking to create a dual-task paradigm. The performance of each component of the dual-task paradigm from single-task performance is then compared between concussed individuals and healthy individuals over time.

Finally, a general summary is provided in Chapter VII, reviewing the individual experiments, with conclusions drawn from the major findings of each. Limitations of the studies are then discussed and suggestions made for future studies. Appendices are provided after the Bibliography, showing the informed consent documents that were used in the experiment.

CHAPTER II

REVIEW OF LITERATURE

Clinical Considerations and Concussion Pathway

A "concussion pathway" schema (Figure 2.1) has been proposed to demonstrate the stepwise path from a primary head insult to permanent brain damage [11]. This pathway considers not only well-documented cognitive deficits, but also recently published motor deficits. Some combination of cognitive and motor deficits can lead to multiple concussions if symptoms are not fully resolved before normal activity ensues. This pathway highlights the importance of a return to normal activity only after the symptoms of a primary concussion have resolved. Two important issues influence this idea. First, the brain is more susceptible to re-injury following an initial concussion. Guskiewicz, et al [5] have found that a person is about three times more likely to sustain a second concussion and 8 times more likely to sustain a third concussion within a three month period after a primary head insult. The second issue to consider is that common symptoms of a concussion can lead to secondary concussions. Reduced information processing (cognitive deficit), imbalance (motor deficit) and an inability to appropriately handle multiple tasks or mediate these tasks (attention deficit) can all contribute to a subsequent concussion-causing injury. This information clearly points out the importance of more rigorous testing following concussion to make an appropriate return-to-play decision.

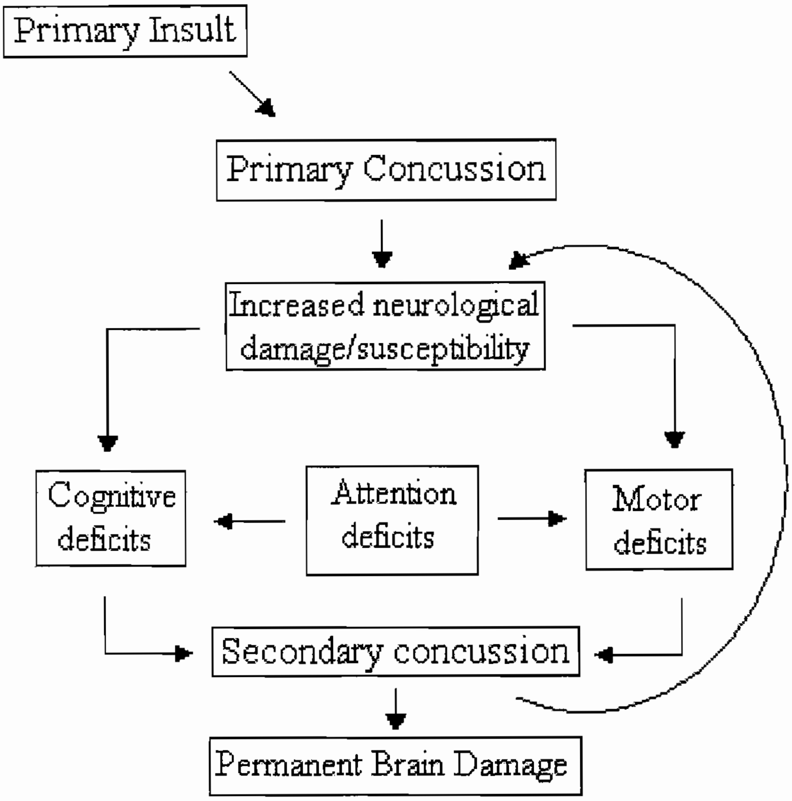

Figure 2.1. Concussion pathway describing the cause of permanent brain damage.

Neuropsychological testing following concussion has been well documented and is routinely performed in the sports setting [12, 13]. Symptoms measured with neuropsychological tests are often reported to return to baseline after a week post-injury [13]. However, relying exclusively on this information for a return-to-play decision should cause concern since such tests are limited to analyses of a subset of the post-concussion symptoms. This reliance is described by Randolph et al [14] and commented on in the Journal of Athletic Training [15]. The use of neuropsychological testing alone may lead to a premature return-to-play decision for an athlete with other residual symptoms, thus increasing the chance of another concussion. Tests of attention and motor function, in addition to neuropsychological testing, are important components of return-to-play decisions. Recent findings of persistent motor dysfunction, gait instability and attentional deficits following mild traumatic brain injury [16-20] suggest that primary reliance on neuropsychological findings, as suggested in some literature [14], may be insufficient to render a judgment on the safe return to unrestricted physical activity.

Attention

While individual components and even subcomponents of attention have been traced with the use of positron emission tomography (PET), and more recently with functional magnetic resonance imaging (fMRI), their dispersion throughout the brain indicates that attention is not necessarily a pot from which we draw the required amount of resources for a given situation. On the contrary, a more accurate description would take note of attention's interconnections to different areas of the brain allowing a quick and accurate response to a stimulus. In this way it can be thought of more like a series of fueling stations for a response, with each fueling station offering its own intricate piece to the response. The dispersion of the components of attention throughout the brain obviously leads to questions about how each is affected by a single biomechanical force with an intricate direction, magnitude, and point of application.

Spatial orientation is most notably needed when one attends to a conversation or unusual noise in auditory situations or to an object in space in visual situations. In testing situations a stimulus can be presented in a certain location. Orienting attention to that location then is measured by reaction times to the stimulus location. Within spatial orientation of attention there are three components. First, one must disengage attention from the area of previous interest. Second, orientation must be shifted to a new location of interest. Engagement of attention to the new target must finally occur. These seem to be the most basic divisions of orientation originally outlined by Posner's work in this area [21]. Each of these processes is thought to occur in specific areas of the brain. By an examination of subjects with parietal injuries, disengaging attention has been linked with the posterior parietal lobe [7]. Subjects with parietal damage were timed in their simple reaction to a light onset with or without a precue. Invalid and neutral trials resulted in remarkably longer reactions times. Disengagement was hypothesized to be the culprit of this effect because movement to the target did not seem to change as long as the cue occurred where the target was to occur. Shifting orientation after disengagement seems to occur in other parts of the posterior parietal lobe. One fMRI study indicates that the superior parietal gyrus is mainly involved in this shifting of attention from one location to another [9]. Another fMRI study indicates that the intraparietal sulcus is of particular importance in shifting orientation and refocusing attention [8]. The superior colliculus and lateral pulvinar seem to be used in shifting and reengaging attention in the presence of a distracting target [22].

The conflict resolution component of attention allows one to use stimuli that are of particular relevance to enhance the response while blocking distracting stimuli that would lead to an incorrect response if utilized. The most widely used test for conflict resolution in formation of a proper response is the Stroop test introduced by John Ridley Stroop in 1935. The conflict is between a response based on color of the word shown and color described by the word. Others have introduced different paradigms to test conflict resolution including a section of the attentional network test (ANT) which requires a choice in arrow directions with surrounding arrows pointing in either a congruent or incongruent direction [23]. No matter the test, the basic premise of testing for conflict is to present two versions of a stimulus: one that aids in the correct response and one that elicits an incorrect response. Time to selection of the correct response between the two conditions would indicate one's ability to ignore conflicting information. One must maintain an understanding of the goal while ignoring interference from habit.

Numerous studies agree that it is the anterior cingulate cortex (ACC) primarily responsible for conflict resolution in such tasks [24, 25]. Swick and Jovanovic took a closer look within the ACC in two patients with specific focal lesions [25]; one with a right mid-caudal lesion and the other with a lesion from left rostral to mid-dorsal. The left mid-dorsal patient was consistently slower in the incongruent trials, indicating this particular location's importance in conflict resolution. However, others have also suggested that the dorsolateral prefrontal cortex also plays a role in executive control for more difficult tasks [26]. They suggest that the ACC maintains the duty of conflict resolution in such tasks, while the dorsolateral prefrontal cortex plays a role in the actual selection of a response.

More like the orienting component, the alerting component of attention shows wide spread functioning, however completely right hemisphere dominant. Studies of right-hemisphere lesioned populations have shown reduced involuntary responses associated with alertness [27] and reduced maintenance of an alert state; vigilance [28]. Both studies implicate the frontal areas of the brain as more important in maintaining this alert state. Posner and Peterson also agree this makes sense since areas of the frontal lobe are entrenched within the bulk of the norepinephrine pathways [22]. Recent imaging has also alluded to right hemisphere of the parietal lobe, thalamus and brainstem activation to maintain alertness [29], however the frontal lobe still showed the largest activations.

The main purpose of alertness in attention is to maintain an arousal level sufficient for quick responses. Precues based on a temporal relationship to the target are often used to test this component. Posner and Peterson propose that an increased alert state can produce rapid responses, but at the cost of higher error rates [22]. Their hypothesis assumes that the alert state is a state where the target threshold has been lowered. By lowering the overall threshold, stimuli that are similar to, but not necessarily the target of interest will activate responses above the lowered threshold and be mistakenly chosen.

Finally, according to Kahneman's model of information processing [30], processing capacity in the human nervous system is limited. When two tasks are presented to an individual, the desired outcome(s) will occur so long as they do not interfere and/or the capacity of the system has not been exceeded. Once the capacity has been reached, there will be a decline in performance. Dual-task experimentation provides researchers with information as to which operations are allocated attentional capacity first [31]. Patients with neurological deficiencies may not possess the attentional capacity to complete both tasks at the same speed or efficiency as during a single-task test because of attention deficits [32-34]. Even in healthy subjects, capacity limits are present if the two tasks are difficult enough [18, 30, 35]. If this is the case, the individual must now divide attention appropriately.

Attention Following Concussion

Even though concussed individuals are often thought to lose focus, conclusive evidence suggesting that there are deficits in the alerting component of attention following concussion is not available. On the contrary, most evidence suggests that concussed individuals perform statistically similar to their healthy counterparts. Current studies of concussions have used measures in the attentional network test to specifically isolate the alerting component [20, 36, 37]. These studies clearly indicate that the alerting component is unaffected by concussion immediately following injury and up to a month later. Why this component of attention is unaffected is still unclear.

The lone contradiction to this research has recently been presented [38]. This study indicates that self-reported fatigue correlated with reduced performance on several standardized attention tests. Even after controlling for the general mood of their subjects, fatigue was still correlated with reduced performance on their most difficult task and higher error rates throughout. They attribute this outcome to decreased alertness, however they do concede that their most difficult task is highly reliant on executive functioning [38]. It is unclear how the two components of attention are related in this study without a similarly difficult test unrelated to executive functioning. This type of paradigm is vital to substantiate their results because the conflict component of attention has shown deterioration due to a concussion.

As mentioned previously conflict resolution falls under the duties of the central executive to choose the correct response. Executive functioning following a concussion or more severe TBI has been well explored in the literature. Assessment of patient's awareness of their own executive dysfunction has even been reported [39]. TBI subjects scored lower on tests of executive functioning and also consistently under-reported their executive dysfunction and reduced attention. Executive dysfunction as a whole has also been shown to coincide with poor performance on tests of problem solving following concussions [40]. While most research in this area tests executive functioning as a whole, certain paradigms are designed to specifically analyze conflict resolution.

Most tests specifically of the conflict component show effects due to concussion as well. While performing a multitude of attentional tests on a TBI group of wide ranging severity, Chan et al. [41] found that reduced Stroop effects occurred in all TBI subjects except those deemed to have a "normal range of attentional performance." In a group of predominantly mild concussed subjects, the same Stroop task interference effect was identified [42]. Likewise, the use of the attentional network task yielded conflict resolution deficits in another group of mild concussed subjects up to one month post injury [20]. These results along with research indicating the location of processing of this conflict component of attention indicate that the anterior cingulate cortex is particularly susceptible to concussive blows.

Spatial orientation has also demonstrated susceptibility to a concussion. A unique study looking at auditory orientation before and after a boxing match showed some interesting results [43]. They showed that receiving blows predominantly to a particular side of the head for an entire boxing match resulted in an immediate increase in error rates when switching attention from the ipsilateral ear to the contralateral ear. Visual spatial orientation of attention to a particular location is deficient after more severe closed head injuries as well [44]. The authors point out that directing orientation had not been mapped to a particular location in the brain, so they suggest that diffuse injury may be the cause of the deficit in their head injury group. More recent research into direction orienting attention has proclaimed areas of the prefrontal cortex as primarily responsible for this action [45]. Others research indicates that concussed individuals are deficient in one of the aspects of orienting attention immediately following the injury, however this returns to normal levels after a week post-injury [20].

Dynamic Balance Control

The center of mass of a system is a specific point at which the system's mass behaves as if it were concentrated. The center of mass is a function of the position of each mass particle that comprises the system. In the case of a rigid body, the position of its center of mass is fixed in relation to the object, but the human body is not a rigid body. The body is constantly in motion and deforming, so the center of mass has to be constantly reevaluated for its new position in space. Previously, measurements of center of mass (COM) location were deemed informative enough to quantify balance control.

However, balance control indicates that the center of mass is resting upon a support and any motion outside of the support will result in a fall.

In stance, the center of mass rests upon the base of support, an area which you have muscular control to move the COM. Manipulation of the position of the center of pressure is how we reposition our center of mass in an inverted pendulum model [46]. As the COM moves forward, the brain receives inputs of this motion from vision of the surrounding, vestibular inputs and somatosensation from a shift in the positions at various joints. Because it is virtually impossible to keep the center of pressure directly under the center of mass in stance, we must employ a strategy to manipulate the center of pressure (COP). It is widely accepted that the ankle strategy is the preferred method in the anterior/posterior direction for most individuals. A continuous cycle of muscle activation at either side of the ankle causes COP motion, resulting in movement of (and attempting to confine) the COM in stance. The same holds true for movement in the medial/lateral direction, for which a hip strategy is used to control COP control. Researchers have demonstrated the muscular control of multidirectional perturbations [47]. Their findings agree with these strategies for A/P and M/L center of pressure control.

Walking stability requires a few more considerations. There are three different phases of walking that we should consider unique to center of pressure control. During gait initiation, the objective of the COP is actually to initiate a fall forward. The body does this with a beginning activation of the dorsiflexors. This moves the center of pressure behind the COM, causing the center of mass to fall forward. Gait termination is just the opposite. The COM is moving forward and the response of the ankle is to activate the plantarflexors to shift the center of pressure anterior enough to arrest the COM within the base of support of the foot. The moment just after a toe off of the trailing foot is also of particular importance in stopping a fall. A feasible stability region that describes the relative (to the height of a person) velocity and relative (to the foot length of a person) distance the center of mass can travel to land and stop within the A/P base of support of the termination foot has been hypothesized and modeled [48]. This is a simple model that assumes a rigid segment between the ankle and the whole body center of mass (no bending at the knee, hip or pelvis), but it accurately portrays that momentum is a major consideration in dynamic movements. The model predicts that as the distance between the COM and base of support is increased, so must the initial velocity to carry the COM to a point over the base of support. Too slow of a velocity will result in the center of mass not reaching the back of the base of support and a backwards fall. Likewise, too fast of a velocity will result in an overshoot of the base of support and a forward fall. Both of these situations assume there is not a second foot to catch the body in case of a fall.

According to Winter [46] we are not afforded the ability to control center of mass acceleration with an ankle strategy during walking. The best we can do is fine-tune the motion of the COM in the A/P direction. Correct placement of the swing foot is our mechanism for stopping a fall in this direction, while control of the posture of particular segments is performed by our muscular control at specific joints. For instance, it is the job of the hip to maintain the posture and balance of the upper body (head, arms and trunk: HAT) unit in both the A/P and M/L directions during walking. The foot in contact with the ground allows the ipsilateral hip to generate a torque. In the case of the A/P direction, hip extensors hold the trunk up while at the same time they are used to progress forward. In the M/L direction the hip abductors create a torque during single leg stance to position the HAT and COM in such a way that they will not fall medially until the swing foot comes down with it. The COM on the hip joint is considered its own inverted pendulum in this manner [49]. The other M/L support for the COM occurs at the subtalar joint (a second inverted pendulum). This moment is too small to actually control the COM, so the acceleration of the center of mass is the major torque against gravity pulling the body down during single leg stance. For walking, it is merely important that the COM remains confined within the lateral COP of each foot. If at any point the COM is lateral to the COP without enough momentum to carry it back medially the inverted pendulum will tip laterally and will have no method to recover.

Recently, measurements of COM trajectory have been stated to provide a more accurate description of how the body moves in space and also provide insight into dynamic balance control mechanisms during locomotion [50]. Considering the work by Pai and Patton [48], an analysis of velocity at maximum separation of the COM from the COP would also yield important information about the balance of the center of mass. Control of the center of mass in the A/P direction is a product of our foot placement and momentum carrying the body through each step. Adjustments in this direction have been used to indicate a safety control over gait [51]. Researchers have expanded this idea to include measurements of the COM location and velocity with respect to the center of pressure (COP) [18, 48, 51]. They have advanced the understanding that COM position with respect to the COP is important to describe which factors might influence balance control in a particular static situation, but the velocity of the COM with respect to the center of pressure can also play a role in whether the body will remain stable due to its momentum. These studies provided a practical and quantifiable way to measure dynamic balance control by examining COM motion with respect to the COP in both the frontal and sagittal planes. But based on Winter's [46] original inverted pendulum modeling of dynamic balance control the COM acts as the head of a pendulum with the fulcrum at the COP. A transition from linear measurements of COM motion to angular measurements about the COP has recently been proposed [52]. This method for testing dynamic balance control allows comparisons between people of different statures. Because these measures are relatively new to the field of biomechanics, they have only recently been employed in testing concussion subjects.

Dynamic Balance Control Following Concussion

The realization that imbalance could result from traumatic brain injury took hold in the mid 90s as patients responding to post-TBI questionnaires consistently reported this among their other disabilities. About half of all participants (severity levels ranging from mild to severe) reported dysfunction due to their injury in a 5 year post-TBI survey and physician assessment study appraising balance impairment [53]. A similar type of scored survey was used to assess the recovery of normal balance in a group of collegiate football players with less severe TBIs [54]. This longitudinal analysis used a few clinical measurements of balance, including sway during tandem stance and while standing on a foam surface. Their results indicated that standing balance control had fully recovered after a single day post-injury, while their array of other deficits persisted up to five days post-injury. Both the functionality and sensitivity of the measurements employed in these studies leave room for questioning.

Creators of the High-level Mobility Assessment Tool (HiMAT) recognized the need for an assessment that was more sensitive to balance deficits and functionally relevant to a younger, more active population [55]. A validation study of the HiMAT indicated that a ceiling effect was not an issue among 103 TBI patients, as it was with 52% of the patients using other traditional scales for assessing mobility and balance impairment [56]. However, the results also indicated a high correlation between the HiMAT and other assessments previously employed, indicating its sensitivity in assessing functional outcomes following TBI.

A measurement of functional outcomes is the end goal of any assessment. Post-TBI questionnaires asking a person to describe the falls that they have experienced due to the concussion seem to be a functionally relevant examination tool to quantify the previous occurrences of instability. Most times, a patient will not report a sense of instability after their TBI. Administered alone, the questionnaire is only insightful if the patient has experienced a fall already or is in such a debilitating state that the deficit may obviously occur. At that point, it may be too late to help the recovery process for those that experience another concussion due to the fall [57]. Assessment surveys discussed above have a strong clinical relevance since most clinicians are not afforded more high-tech assessment tools, and these tests could be sideline administered. However, these assessments are still subjective and are exposed to inter-examiner variability. This is why a more objective quantification of balance impairment following a concussion is needed.

Kinematic and kinetic measures of standing stability offer increased quantification. One of the earlier paradigms given to TBI patients involved posturography under various conditions [58]. Sway in these tasks was measured in each direction by the COP velocity rather than actual excursion. Patients displayed more sway and worse performance in weight shifting compared to controls. Decreased performance during weight shifts suggested a deficit in coordinating movements and increased sway suggested a lack of stability control as well following TBI. Decreased performance in the secondary task also suggested that postural instability could adversely affect cognitive performance following a TBI.

A more functional paradigm using seating posturography incorporated a reaching task [59]. The direction and magnitude of COP excursion compared to that needed was measured in ratio form as patients and controls performed target reaching. Patients had longer response times and larger amounts of COP excursion. Similarly an examination of COP was performed in different stance conditions and then compared with functional assessments of walking and reaching tasks [60]. Interestingly, the group found no correlation between measures of COP excursion and their functional assessments. These results questioned the efficacy of either the functional assessments currently used by clinicians and/or the value of COP measurements in standing stability.

The development of a standardized and validated method of measuring postural control and the different sensory components it uses helped to better understand stability issues following concussion. A group out of the University of Georgia has recently employed the NeuroCom Smart Balance Master testing device in their examination of standing balance control [61, 62]. The group first used the NeuroCom and other neuropsychological tests to measure differences in AAN severity grades [62]. The sensory organization test of the NeuroCom allowed the group to measure how vision, somatosensation and vestibular inputs are affected following TBI. The "limits of stability" test using the NeuroCom allowed the group to measure how well a TBI group can regain control of their COM after a perturbation from different directions. While they did not report a deficit in any one component of sensory organization, they found that a reduced composite score of balance corresponded with injury severity. Reaction times to a perturbation also corresponded with injury severity. The researchers then began to examine the stability measurements of the NeuroCom in combination with a secondary cognitive task in a non-concussed group for an eventual assessment of concussion [61]. They found that balance scores actually improved during a dual-task condition in healthy individuals. The authors attribute this to the healthy individual's ability to control their stability in instances when attention must be shared between tasks.

Tests of standing balance control following a concussion have been able to better quantify stability as compared to the clinical assessment. Development of the NeuroCom has also aided in assessments of the different components used in stability. However, these tests are still only measuring performance during standing. It is rarely reported that an individual suffering from a TBI will actually have functional issues with standing balance control (except in cases of prolonged standing). Therefore, the functionality of this testing paradigm is still in question. It seems more likely that stability issues suffered by concussed individuals are more prevalent while performing a whole-body dynamic motor task. That being the case, testing paradigms using a dynamic motor task seem to be more functional assessments of stability following concussion.

A group out of the Mayo Clinic has recently used clinical assessments, standing posturography (with the sensory organization test) and a gait analysis to compare assessment techniques for TBI subjects [63, 64]. Results from this group's study indicate a high correlation between physical impairments described by the TBI subjects and reduced scores on the sensory test designed to measure one's ability to utilize only vestibular input, while ignoring somatosensation and visual inputs. The physical disability score also correlated with reduced A/P motion. The functional disability index correlated with M/L COM velocity. TBI subjects showed reduced A/P motion and increased M/L motion compared to healthy controls. This analysis indicates the significance of a gait analysis in assessments of perceived impairments in a more severe TBI group.

Other groups have recently attempted to make gait tasks more functional to everyday situations. Tripping over an obstacle had previously been blamed for the occurrence of most injuries from falls [65]. Therefore, obstacle crossing has been recently used in TBI groups. McFadyen and colleagues studied the effect of an obstacle-crossing task while walking following traumatic brain injury and compared it with clinical assessment techniques [35]. All but one of their subjects scored perfectly on the Berg balance test. However, slower gait velocities, increased obstacle clearance and decreased stride lengths led their group to conclude that subjects with a TBI adopt a cautious gait during obstacle-crossing. Another analysis from the Mayo Clinic addressed the effects of obstacle crossing on stability [18]. They performed a similar study, but measured the whole body COM motion of TBI patients during the crossing of several different obstacle heights. Various obstacle heights were used to simulate different obstacles in the environment. Subjects with TBI and controls showed similar gait patterns during unobstructed walking trials, indicating that this task might not always be sensitive in detecting changes in stability. Gait velocities and stride lengths decreased in TBI subjects compared to controls during obstructed walking. Medial/lateral COM sway and instantaneous velocity at the peak COM-COP separation increased in TBI subjects, but not in healthy controls, as obstacle height increased. This study indicated that frontal plane instability can be identified with an obstacle crossing task.

Other functional tasks that have been recently used to assess the ability of a TBI subject to remain stable include performance of a simultaneous cognitive task in a dual-task paradigm. These types of paradigms have been described as most similar to real-world conditions [66, 67]. Some of the earliest research using a dual-task paradigm in this area was performed on subjects with debilitating TBIs [68]. While the dual-task paradigm resulted in few changes for healthy controls, TBI subjects showed reduced performance on cognitive tasks and increased spatial-temporal gait variability in the dual-task conditions. In a similar study, cognitive variables as well as spatial-temporal gait variable showed reductions during a dual-task situation following a severe TBI [69].

Lately, studies have used previously validated quantifications of gait stability, including COM and COP motion. The research has also been extended to those suffering more mild forms of TBI. Our own research has compared cognitive tasks of varying difficulty [70] and compared this dual-task paradigm with the often used obstacle crossing paradigm [11] immediately after concussion. From this research, we have learned that a more difficult dual-task paradigm was more sensitive to the effects of concussion immediately following the injury. Concussed subjects displayed a more conservative gait, but also more medial/lateral balance deficits in the difficult dual-task paradigm following the concussion. Our work has also extended the analysis to one month after the injury [19]. These findings suggest that the conservative adaptation to the dual-task paradigm remains, while medial/lateral balance control shows a steady return to normal up to 14 days post-injury.

Summary

In conclusion, there are several components of attention that have been examined following a concussion. The alerting component that maintains a temporal arousal has shown little to no deficits following a concussion. The conflict resolution component enabling one to ignore distracting information during the formation of a correct response seems to be most susceptible for the longest period of time. The orienting component of attention allows for the disengagement, direction, shift and reengagement of attention to a location. This component of attention has also shown some susceptibility to concussion, however, the general assumption is that it may not be nearly as prolonged as conflict deficiencies. Finally, dividing attention seems to lead to deficits in balance control.

Further biomechanical investigations into a concussed individual's ability to maintain balance control during gait under various conditions need to be performed to understand how exactly balance control is effected by concussion and determine if we can precisely detect crucial disabilities. A better understanding of the interaction between these biomechanical measurements and attention is important for the development of effective interventions aimed at prevention of subsequent concussions. These are the areas of primary focus in this doctoral dissertation.

CHAPTER III

IMMEDIATE VS. LONG-TERM EFFECTS OF CONCUSSION ON BALANCE CONTROL

Introduction

Although concussive incidents rarely result in any patient-reported long-term symptoms [71], studies have found that symptoms may last longer than that reported by the patient; even long after a return to normal unrestricted activities [17, 19, 72]. Although the specific causes of repeated concussions is still unclear, it is our contention that long-term deficits in dynamic motor function [17-19, 72], such as balance control during walking, may be one contributing factor. Multiple concussions occurring with unresolved symptoms can lead to permanent brain damage or increased probability of fatality depending on the time interval between concussive episodes [57].

Neuropsychological testing following concussion has been well documented and is routinely performed at least in the sports setting [12, 13]. Symptoms measured with neuropsychological tests are often reported normal after 14 days post-injury. However, findings of motor dysfunction, gait imbalance and attentional deficits during motor/cognitive dual-task tests have contradicted this quick (within two weeks) return to normal functioning. A group of predominately mild traumatic brain injury (mTBI) subjects were reported displaying deficits in finger tapping up to a year post-injury [72]. Children with mTBI displayed balance deficits up to 12 weeks post-injury [17]. Severe TBI subjects have shown balance control deficits while performing obstacle crossing approximately a year after injury [18]. Concussed college-aged adults showed decreased dynamic balance control during an attention dividing task a month post-injury. [19].

Recently, tests of balance control during an attention dividing task have been proposed as an alternative method for assessing college-aged individuals following concussion [11, 70]. When compared to other gait scenarios, gait with a secondary question and answer task was found to better differentiate a concussed individual's changes in balance control from healthy controls within two days post-injury. While obstacle crossing was deemed ineffective in distinguishing concussed individuals immediately following injury in the same study [11], others have previously used obstacle crossing tasks to successfully detect balance control deficit in more severely injured subjects months after the injury [18, 35].

To our knowledge, a longitudinal examination of balance control comparing two balance perturbing gait tasks (divided attention walking vs. obstacle crossing) has not been performed with concussed individuals. Such information would uncover dynamic balance deficits following concussion during both tasks, while simultaneously identifying the most sensitive test to such balance deficits. If deficits do exist and tests for such deficits are clinically implemented then concussed patients may have a more exact timeframe to limit motor activities and avoid subsequent concussion

The purpose of this study was to examine dynamic balance control over a one month period, using gait protocols that have been previously used, to determine a gait scenario that can effectively detect changes in balance control of concussed individuals and can be used to track recovery. Based on previous reports, we hypothesize that a concurrent cognitive task will most effectively accomplish both of these purposes.

Methods

Thirty concussed subjects (mTBI) were referred to testing by the student health center or athletic team physicians/ATCs of the University of Oregon. MTBIs (14 females/16 males; age = 21.5 ±3.3 years; mass = 83.2 ±24.7 kg; height = 176.7 ±10.8 cm) were diagnosed with grade II concussions as defined by the American Academy of Neurology Practice Parameters [73], which entails symptoms lasting longer than fifteen minutes, but no loss of consciousness. Exclusion criteria included preexisting abnormalities in gait or cognition. Sixteen mTBI participants had a previous concussion a year or more prior to testing but none indicated any lingering symptoms. Subjects in this study ranged from non-athletic to intercollegiate athletes. All subjects participating in this study were still participating in their particular activity at the time of injury at either the college or professional level, or have since graduated and are no longer active.

Thirty control subjects were matched by gender, age (21.7 ±3.1 years), mass (82.6 ±23.9 kg), height (175.9 ±10.4 cm), level of education and athletic participation. Exclusion criteria were the same as that for mTBI subjects, in addition to exhibiting common symptoms of concussion described by Collins et al [74]. Ten controls had a previous concussion more than 1.5 years prior to this study, but none complained of any lingering effects and were functioning normally in society and academics. Approval for the use of human subjects was granted prior to testing by the university Institutional Review Board. Written and verbal instructions of testing procedures were provided and written consent was obtained from each subject prior to testing.

Twenty-nine retroreflective markers were attached to anatomical landmarks [51]. Three dimensional marker trajectories were collected with an eight camera motion tracking system (MotionAnalysis Corp.) at 60 Hz. The cameras were positioned surrounding an eight-meter walkway. Ground reaction forces and moments were collected at 960 Hz with two in-ground force plates (Advanced Mechanical Technologies Inc.). A PVC pipe (1/2" diameter, 1.3 m length) set atop two adjustable uprights between the two force plates was used as an obstacle.

The first testing (day 2) of mTBI subjects occurred within 48 hours post-injury (35.8 ±13.1 hours). Data collection started with a single-task level walking session (LEVEL). Subjects were asked to walk at a comfortable self-selected pace while barefoot. Several practice trials were allowed so that subjects could become accustomed to walking with the marker set.

Shorter and taller obstacle crossings representing common obstacle heights experience daily were then performed in two blocks. During short obstacle crossing (OBS) the obstacle was set to a 4 cm height. During tall obstacle crossing (OBT) the obstacle was set at 10% of the subject's body height. The final trial block was a divided attention task (Q&A). Subjects performed unobstructed gait while continuously responding to a question posed at the beginning of each trial. Questions included: spelling a common five-letter word in reverse, continuous subtraction by a certain number, and reciting the months of the year in reverse order [11, 19, 70, 75, 76]. At the beginning of each trial the subject was given the specific task for that trial (e.g. count backwards by sevens starting at ninety-three). The subject then started walking and answering at the same time and stopped answering at the end of the walkway. Each testing session lasted about 30 minutes with breaks between trial blocks. MTBI subjects performed the same set of tasks at the approximate 6th day, 14th day and 28th day post-injury. Controls were tested at similar time intervals.

Marker trajectories were filtered with a low-pass fourth order Butterworth filter at a cutoff frequency of 8 Hz. Marker position data were used to locate the segmental center of mass (CoM) of a thirteen-link model including: head, trunk, two upper arms, two lower arms, pelvis, two thighs, two shanks and two feet, based on Dempster's anthropometric data [77]. A weighted sum method was used to calculate the whole body CoM during each time point. CoM motion data were analyzed between the first heel strike on to the first force plate to the next heel strike of the same foot. CoM velocities were estimated with the use of Woltring's generalized cross-validated spline algorithm [78]. Center of pressure (CoP) data were calculated from force plate data.

A model of how balance is maintained through proper positioning of the CoM and momentum of the CoM over the base of support has been established as a measure of dynamic balance control [46, 48]. In this study of walking balance control, CoM sagittal and coronal plane range of motion (AP ROM and ML ROM), and peak velocities in the anterior-posterior (AP V) and mediolateral directions (ML V) were identified. CoM data were synchronized with the CoP data to find the maximum horizontal separation distance between the CoM and CoP in both the sagittal plane (APmax; Figure 3.1a) and coronal plane (MLmax; Figure 3.1b). Data from three to five successful trials were averaged together for each group, day and task to complete the statistical analyses.

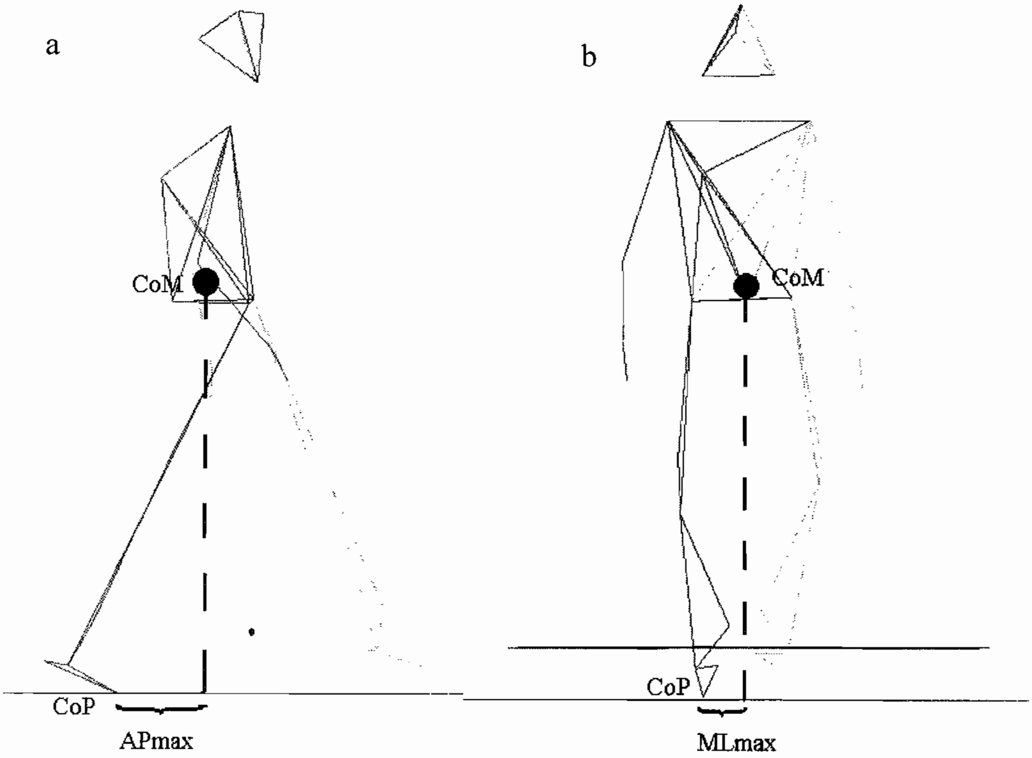

Figure 3.1. The maximum distance between the vertical projection of the center of mass (CoM) on to the ground and the center of pressure (CoP) in the (**a**) sagittal plane is APmax and (**b**) coronal plane is MLmax

Appropriate assumptions for mixed ANOVAs were analyzed and considered tenable. Upon assumptions being met, a three-way mixed model analysis (2 groups, 4 tasks and 4 days) with repeated measures (alpha = 0.05) was conducted using SAS 9.1

(SAS Institute Inc., Cary, NC). Follow-up pairwise comparisons with adjustments for multiple comparisons were performed. Alpha levels were set *a priori* at 0.0167 for pairwise comparisons based on recommendations about error rates relative to individual family size [79].

Results

The results for sagittal plane balance control clearly indicate that concussed individuals had less forward motion immediately after injury when having to perform a divided attention gait task. A three-way interaction in AP ROM ($p = 0.0030$) showed that mTBIs had less sagittal plane CoM displacement than controls on day 2 during the Q&A task ($p = 0.0143$). A group-by-day interaction in AP V ($p < 0.0001$) showed that mTBIs also significantly had a slower peak anterior CoM velocity on day 2 during the Q&A task ($p = 0.0135$; Table 3.1). APmax also showed a group-by-day interaction ($p = 0.0187$), however further analysis only determined a trend of mTBIs allowing less separation between their CoM and CoP in the anterior direction on day 2 during the Q&A task ($p = 0.0381$).

The results for coronal plane balance control indicate that concussed individuals initially are not different from controls, but two weeks after injury they begin to have less coronal plane motion while crossing an obstacle. A three-way interaction in ML V ($p = 0.0228$) showed that mTBIs had significantly slower sideways peak velocities by day 14 for the shorter obstacle crossing task ($p = 0.0143$; Table 3.1) and by day 28 for the taller obstacle crossing task ($p = 0.0128$). A group-by-day interaction in MLmax ($p < 0.0001$)

showed that mTBIs also reduced their CoM-CoP separation distance in the medial/lateral direction by day 28 for both obstacle crossing heights (OBS: *p* = 0.0006; OBT: *p* = 0.0018; Table 3.1).

Table 3.1. Mean values and standard errors of COM variables. The two group means within a boxed area are significantly different from each other.

Variable	**Task**	**Group**	**Time (days)**			
			2	**6**	**14**	**28**
AP V (m/s)	LEVEL	mTBI	1.39 (.02)	1.49 (.02)	1.52 (.02)	1.53 (.02)
		Cont.	1.42 (.02)	1.48 (.02)	1.48 (.02)	1.51 (.02)
	Q&A	mTBI	1.25 (.02)	1.38 (.02)	1.42 (.02)	1.44 (.02)
		Cont.	1.33 (.02)	1.41 (.02)	1.43 (.02)	1.45 (.02)
	OBS	mTBI	1.39 (.02)	1.47 (.02)	1.49 (.02)	1.51 (.02)
		Cont.	1.43 (.02)	1.48 (.02)	1.49 (.02)	1.50 (.02)
	OBT	mTBI	1.34 (.02)	1.44 (.02)	1.45 (.02)	1.46 (.02)
		Cont.	1.40 (.02)	1.47 (.02)	1.45 (.02)	1.48 (.02)
MLmax (m)	LEVEL	mTBI	0.080 (.003)	0.080 (.003)	0.078 (.003)	0.079 (.003)
		Cont.	0.076 (.003)	0.079 (.003)	0.078 (.003)	0.084 (.003)
	Q&A	mTBI	0.084 (.003)	0.082 (.003)	0.081 (.003)	0.077 (.003)
		Cont.	0.080 (.003)	0.080 (.003)	0.082 (.003)	0.086 (.003)
	OBS	mTBI	0.079 (.003)	0.075 (.003)	0.077 (.003)	0.072 (.003)
		Cont.	0.076 (.003)	0.076 (.003)	0.084 (.003)	0.087 (.003)
	OBT	mTBI	0.079 (.004)	0.076 (.004)	0.080 (.004)	0.074 (.004)
		Cont.	0.075 (.004)	0.078 (.004)	0.085 (.004)	0.090 (.004)
MLV (m/s)	LEVEL	mTBI	0.134 (.004)	0.132 (.004)	0.134 (.004)	0.132 (.004)
		Cont.	0.133 (.004)	0.140 (.004)	0.138 (.004)	0.135 (.004)
	Q&A	mTBI	0.148 (.007)	0.148 (.007)	0.145 (.007)	0.145 (.007)
		Cont.	0.149 (.007)	0.159 (.007)	0.150 (.007)	0.149 (.007)
	OBS	mTBI	0.144 (.005)	0.143 (.005)	0.139 (.005)	0.135 (.005)
		Cont.	0.146 (.005)	0.151 (.005)	0.157 (.005)	0.148 (.005)
	OBT	mTBI	0.157 (.005)	0.155 (.005)	0.147 (.005)	0.148 (.005)
		Cont.	0.156 (.005)	0.159 (.005)	0.164 (.005)	0.168 (.005)

Discussion

Single task level walking was not able to effectively distinguish the two groups at any time point in the recovery process. Previous reports have consistently demonstrated a tendency for concussed individuals to adopt a more conservative gait strategy by either walking slower and/or allowing less motion of the CoM in the sagittal plane immediately following the concussion [11, 19, 70, 76]. These current results showed a trend of this conservative gait strategy adopted during level walking immediately after the concussion. We believe that relatively minute changes in gait during level walking were indistinguishable when comparing so many tasks with relatively large differences between groups during other tasks. Previous analyses of gait have yielded some inconsistent results for coronal plane motion during single task level walking. Some indicated group differences and some refuting difference [11, 19, 70, 76]. Current findings and inconsistencies in the literature may suggest that an analysis of single-task unobstructed gait cannot adequately distinguish concussed individuals and will not be able to consistently and accurately track their recovery.

Immediately following a concussion, level walking with a concurrent cognitive (Q&A) task was able to distinguish concussed individuals from uninjured controls better than other gait tasks. Our results on day 2 during the Q&A task are in accordance with previously reported results that not only showed reduced gait velocity due to a concussion, but also reduced sagittal plane motion of the CoM to indicate a conservative gait adaptation to this task [11, 19, 70, 76]. Center of mass trajectories have been previously described as providing insight specifically into dynamic balance control mechanisms [48, 50]. By day 6 the Q&A task no longer detected any group differences suggesting that the average concussed individual had recovered enough from any attentional processing deficits they might have been inflicted with immediately following the concussion that balance control was no longer affected. This quick return to normal is in line with many neuropsychological findings [12, 80]. The spatial orientation component of attention has also been reported to return to normal by five days post-injury, while the executive function component of attention still showed signs of deficit up to a month post-injury [20]. The combination of slower processing speed, deficits in the ability to spatially orient attention and deficits in switching attention between tasks have been used to describe the increased challenge that concussed individual are subjected to in a dual-task walking situation [37]. The fact that only spatial orientation of attention improves by five days post-injury while other aspects of attention remain disabled up to a month post-injury [20] in combination with our results may indicate that either the remediation of any part of attention helps in performance during dual-task walking or that remediation of spatial orientation of attention is correlated with the recovery of other attention components that would be more likely to aid in Q&A task performance. While improved performance by 6 days post-injury is contradictory to a previous report that showed reduced sagittal CoM motion in gait even up to a month post-injury when attention was divided [19], a trend in our data may suggest similar results. The conflicting statistical significance could be an indication of the heterogeneity in concussive symptoms between subjects, further supporting our recommendation for individual motor/attention tests prior to a return to activity.

The two groups displayed no statistical differences in CoM motion when performing obstacle crossing in the first week of testing. Similar findings have also concluded that obstacle crossing was less effective at distinguishing mildly concussed individuals immediately following injury [11]. However, this longitudinal analysis of obstacle crossing revealed interesting findings at the two- and four-week testing sessions. By day 14, concussed individuals showed the first signs of statistically different mediolateral CoM motion. They had reduced mediolateral peak velocities of the CoM by day 14 and also reduced mediolateral separation of the CoM and CoP on day 28. Both of these indicate that concussed individuals conservatively control mediolateral balance based on a distance-velocity model of the CoM with respect to the base of support [48]. Others have also suggested eventual conservative balance control during obstacle crossing [35]. By reducing CoM motion in the coronal plane, sideways imbalance might be better avoided [70].

There are several possible reasons as to why mediolateral control mechanisms are adopted only by 14 days after concussion. One possibility is a reacquisition of mediolateral balance control. This hypothesis implies group differences in mediolateral balance control prior to day 14. The data however indicated that both groups had similar frontal plane CoM motion during the first two testing sessions. Nevertheless, similar values might not necessarily indicate similar performance if one group (mTBI) was required to apply greater effort (as has been previously suggested for cognitive test performance by concussed individuals [81]) in controlling mediolateral balance during walking, while the control group accomplished the same task with less effort. Examining obstacle crossing with simultaneous Q&A performance might be able to shed light on this premise. The second possibility is that concussed individuals felt no need for greater demand in mediolateral balance while performing obstacle crossing prior to day 14. Poor decision making [82] and a lack of full task/environmental awareness [83] immediately following the concussion may have led to a false sense of ability and security during obstacle crossing. Only after this commonly reported "mental fogginess" subsided did concussed individuals understand the importance of a safe obstacle crossing strategy when taking into account their reduced strength and coordination [74] needed to arrest the body during a possible trip and desire to avoid re-injury. The final possibility is that confining mediolateral CoM motion could be due to increased comfort performing this particular task. Anxiety for several weeks following mild brain injury has been documented [84]. Gradually increasing comfort with their ability to safely cross over the obstacle without obstacle contact may allow the concussed individuals to focus more attention on medial/lateral balance control. Further analyses of obstacle crossing parameters may be used to test these hypotheses.

A major limitation to our study is that control subjects did not perform similarly each day. Although not statistically significant, control subjects also displayed a change in gait performance over time indicating a decrease in performance anxiety each subsequent testing session. However, all subjects were tested in similar conditions, so any change in performance due to anxiety would be expected in both groups rather than just one. This indicates that normal changes in performance due to comfort with the testing protocol are also imbedded in the longitudinal curves for concussed subjects. Another limitation is the inclusion of individuals with previous concussions within both groups. This was unavoidable given the limited sample size in the concussed group and the matching criteria in the control group. We however believe that not allowing individuals to participate if they had a concussion within a year prior is sufficient in excluding individuals still suffering from previous symptoms since there are no reports of symptoms of a mild (no loss of consciousness) concussion lasting longer than one year.

Conclusions

Our findings indicated that a divided attention task performed during unobstructed gait was only able to better distinguish conservative gait adaptations immediately following a concussion. By day 6, attention had seemed to recover to the point at which the attention dividing task was no longer effective in perturbing balance control in concussed individuals. By day 14, a more conservative control of mediolateral CoM motion was observed in the concussed group during obstacle crossing. An attention dividing task and obstacle crossing task seem to detect changes in gait adaptations at different times in the recovery process. The inclusion of at least an obstacle crossing task may be advantageous in clinically detecting a recovery of functional balance control during gait based on data from this study. This information may someday lead to the regular inclusion of appropriate and clinically executable dynamic balance control tests after concussion. However, a longer longitudinal study where obstacle crossing returns to normal is recommended to determine that functional balance control is fully recovered.

Bridge

This chapter summarized how balance control of concussed individuals differed from healthy control individuals during individual tasks. The tasks used in this study were indicative of those performed by the limited number of researchers studying dynamic balance control of brain injured individuals. This was the first to actually compare tasks performances following concussion in a longitudinal analysis. Concussed individuals used a unique pattern of balance control for each of the particular perturbations to normal level walking. The logical next step is to now study how concussed individuals maintain balance control during a more challenging task that combines the perturbations at the same time. From this we can determine if this increased challenge further distinguishes concussed individuals from healthy control or if there is a ceiling at which the perturbation becomes too challenging for even a healthy individual.

CHAPTER IV

COMBINED MOTOR AND COGNITIVE TASK EFFECTS FOLLOWING CONCUSSION

Introduction

Many well defined neurological diseases are clinically identifiable via a simple paradigm that imposes an appropriate perturbation. Identifying cerebral palsy or Parkinson's involves a particular set of motor and reflex tests involved in walking or stability. In advanced cases, diagnosis can be quite easy because there is such an extreme difference between the performance of patients and healthy individuals. Other diseases like mild forms of multiple sclerosis or concussion are not as easy to diagnosis because the difference between these individuals and healthy individuals are minute, but obviously not insignificant because they can lead to severe outcomes if ignored. Researchers interested in identifying a particular testing protocol to accurately distinguish a patient population face the challenge of using a paradigm that provides sufficient difficulty, but not so difficult as to compromise the performance of all individuals, even the healthy.

Concussions are also transient, so diagnosing a complete recovery after injury can prove just as challenging, if not more so because of the gradual nature of the recovery in some cases. Current protocols for diagnosing and treatment of a concussion include an examination of the symptoms, and then precautionary rest until these symptoms resolve. Under some conditions neuropsychological testing is performed as a diagnostic tool and a measure of recovery. Although warranted, neuropsychological tests can only identify a handful of symptoms. Often symptoms related to balance, coordination, strength, or any unexamined cognitive processes (like attention interference with other tasks) are ultimately not examined when neuropsychological testing is relied upon for diagnosis and management. If a misdiagnosis of the occurrence of concussion or misdiagnosis of complete recovery following concussion occurs then patients are left susceptible to an increased chance of permanent brain damage or fatal outcome from subsequent concussions [57]. A diagnostic protocol completely measuring both cognition and motor performance is imperative.

Neuropsychological testing following concussion has been well documented and is routinely performed in the sports setting [12, 13]. Symptoms measured with neuropsychological tests are often reported to return to baseline within 14 days post-injury. However, findings of motor dysfunction, gait instability and attentional deficits during motor/cognitive dual-task tests have contradicted this quick return to normal neurological functioning. A group of predominately mild traumatic brain injury (mTBI) subjects were reported displaying deficits in finger tapping even up to a year post-injury [72]. Children with mTBI displayed balance deficits up to 12 weeks post-injury [17]. Severe TBI subjects have shown instability while performing obstacle crossing approximately a year after injury [18]. Concussed college-aged adults showed decreased gait stability during an attention dividing task a month post-injury [19].

Cognitive tests have been incorporated with gait to provide dynamic attentional tests in a dual-task setting [31, 67, 85, 86]. Cognitive/motor dual-task situations have been described as most similar to real life scenarios [66, 67, 76]. Recently, tests of gait stability during an attention dividing task have been proposed as an alternative method for assessing college-aged individuals following concussion [11, 70]. When compared to other gait scenarios, gait with a secondary question and answer task was found to better differentiate the changes in sagittal and frontal center of mass stability within two days post-injury. While obstacle crossing at 10% of body height has been deemed inconclusive in distinguishing concussed individuals immediately following injury [11], others have used the task successfully in distinguishing more severely injured subjects months after the injury [18, 35]. There is no current literature describing concussed performance in a task with increased cognitive and motor difficulty.

The purpose of the current study was to examine gait stability and secondary task performance as task difficulty increases in the cognitive domain, motor domain, or both as performed by healthy individuals and those suffering from mild traumatic brain injury. The overall goal is to find a gait task that discriminates the effects of a concussion and monitor performance with it at different points during recovery. Based on our previous analyses [11], we suspect a ceiling effect in gait instability as task difficulty increases, but at the cost of a diminished secondary task performance. We also hypothesize that any differences between the two groups would diminish as recovery progresses from the subject concussion.

Methods

Thirty concussed (mTBI) subjects (13 females/17 males; age = 21.5 ±3.3 years; mass = 83.64 ±24.7 kg; height = 177.42 ±11.5 cm) were referred to testing by the student health center or athletic team physicians/ATCs of the University of Oregon. Subjects were required to have sustained a grade II concussion as defined by the American Academy of Neurology Practice Parameters [73]. Under these guidelines, a grade II concussion entails transient confusion and symptoms lasting longer than fifteen minutes, but no loss of consciousness. Exclusion criteria included preexisting injury or surgery that affects normal gait performance or cognitive abilities. Individuals previously inflicted with a concussion within a year prior to testing were also excluded.

Thirty control subjects were recruited from the University of Oregon student body. Controls were matched by gender, age, mass, height, level of education and athletic participation (13 females/17 males; age = 21.8 ±3.2 years; mass = 82.35 ±24.6 kg; height = 176.23 ±10.9 cm). Exclusion criteria of control subjects were the same as the exclusion criteria for concussion subjects, with the additional criterion that control subjects not exhibit any of common symptoms of concussion (e.g. vision problems, nausea, headaches, etc.) described by Collins et al [74]. Approval for the use of human subjects was granted by the university Institutional Review Board. Written and verbal instructions of testing procedures were provided and written consent was obtained from each subject prior to testing.

All data was collected in the Motion Analysis Laboratory of the University of Oregon. Twenty-nine retroreflective markers were attached to anatomical landmarks [51]. Three dimensional marker trajectories were collected with an eight camera motion tracking system (MotionAnalysis Corp., Santa Rosa, CA) at a sampling frequency of 60 Hz. The cameras were positioned surrounding an eight-meter walkway. Ground reaction forces in three orthogonal directions and moments about the three axes were collected at a sampling rate of 960 Hz with two in-series strain gauge force plates (Advanced Mechanical Technologies Inc. Watertown, MA) flush with the top surface of the floor in the center of the walkway. A PVC pipe (1/2" diameter, 1.3 m length) set atop two adjustable uprights between the two force plates was used as an obstacle during obstacle crossing trials. This obstacle design was fashioned in such way to easily come apart if contacted to avoid tripping.

The first testing (day 2) of concussed subjects occurred within 48 hours post-injury for all subjects. Data collection started with a normal walking session (LEVEL). Subjects were asked to walk at a comfortable self-selected pace while barefoot. Several practice trials were allowed so that subjects could become accustomed to walking with the marker set and the starting spot could be adjusted by the proctor to insure that subjects hit each force plate with the entire foot. Subjects were not informed as to the reason for position adjustment so that conscious adjustments in gait could be avoided.

The second task performed in this analysis was obstacle crossing (OB) over a single, fully-visible obstacle in the middle of the walkway set at 10% of each subject's body height. The third task was a divided attention task (Q&A). Subjects performed unobstructed gait while continuously responding to a question posed at the beginning of each trial. Questions included common tests from a clinical mental status examination: spelling a common five-letter word in reverse, continuous subtraction by a certain number, and reciting the months of the year in reverse order [11, 19, 70, 75, 76]. The order and specifics of each task were not shared with the subject prior to testing. Only at the beginning of each trial were the subject given the specific task for that trial (e.g. count backwards by sevens starting at ninety-three, or months of the year in reverse starting at February). The subject then started walking and answering at the same time and stopped answering at the end of the walkway. The final task performed was a combination of the obstacle crossing task with the Q&A task (D-OB).

Each walking trial lasted approximately 8 seconds. The subject then returned to the starting position and waited several seconds for the next trial to begin. Subjects rested for several minutes between trial blocks. Each subject performed approximately 30 total trials. Concussed subjects performed the same set of tasks at approximately the 6th, 14th and 28th day post-injury. Controls were tested at similar intervals.

Marker trajectories were filtered with a low-pass fourth order Butterworth filter at a cutoff frequency of 8 Hz. Marker position data was used to locate the segmental centers of mass (CoM) of a thirteen-link model including: head, trunk, two upper arms, two lower arms, pelvis, two thighs, two shanks and two feet, based on Dempster's [77] anthropometric data. A weighted sum method was used to calculate the whole body CoM from segmental CoMs during each time point. CoM data was analyzed between the first heel strike on to the first force plate to the next heel strike of the same foot. CoM velocities were estimated with the use of Woltring's generalized cross-validated spline algorithm [78]. Center of pressure (CoP) data was calculated for all time points that the subject was only in contact with a force plate. Laboratory written programs (Motion Analysis Lab, University of Oregon) in Matlab 7.0 (Mathworks Inc., Natick, MA) were used to complete the processing of the data during one complete stride.

Inclination angles were calculated as the angle from the CoM, down to the CoP and back up to the vertical (Figure 4.1). CoM data were synchronized with CoP data for a complete stride to find the peak inclination angles in the sagittal and coronal plane.

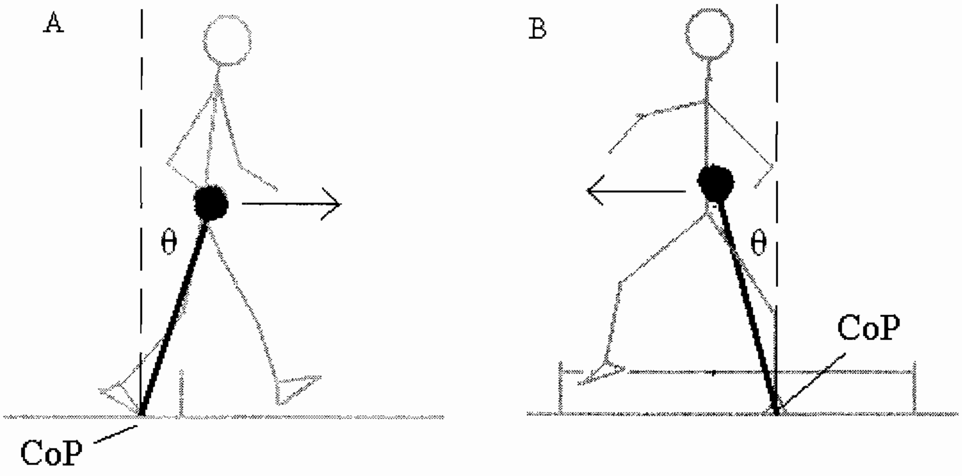

Figure 4.1. The inverted pendulum model during walking indicating the inclination angle (θ). The head of the pendulum is the CoM and the pivot is the CoP. (A) A sagittal plane view showing the peak anterior inclination angle. (B) A frontal plane view showing the peak medial inclination angle.

The posterior and anterior peak angles were then summed to find the sagittal plane angular range of motion (SR, Figure 4.2). The medial peak angle from the left foot was summed to that of the right foot to find a frontal plane angular range of motion (FR, Figure 4.2). Peak velocities of the CoM in both the sagittal and frontal plane (SV, FV) were identified. Number of correct responses, responses attempted and accuracy were recorded from the Q&A and D-OB tasks.

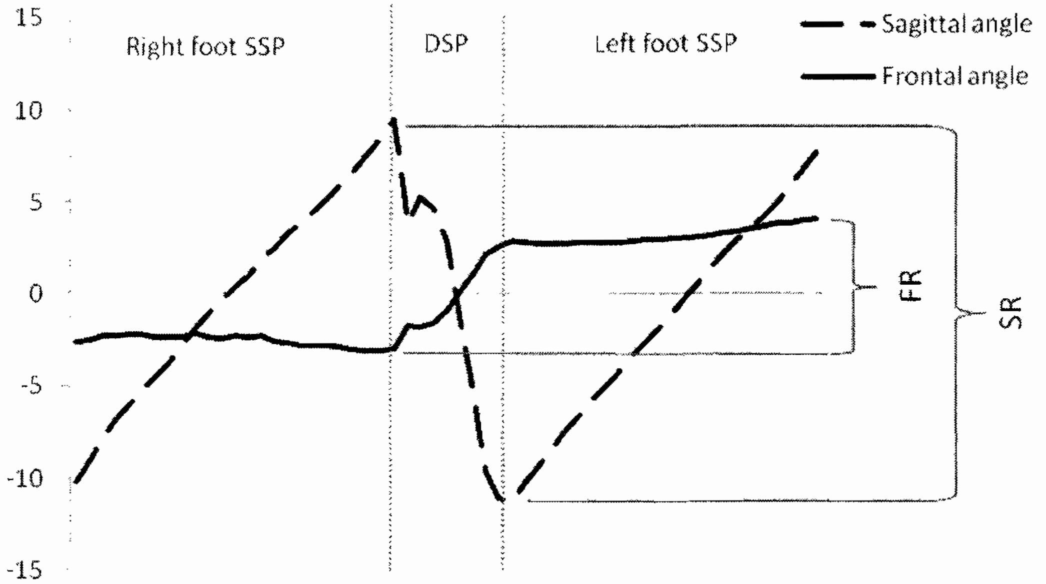

Figure 4.2. The typical angular motion of the COM with respect to the COP from toe-off of the lead foot to heel-strike of the trailing foot in both the sagittal plane and frontal plane. SSP is single support phase. DSP is double support phase. The FR and SR are displayed on the right

A three-way mixed model analysis of variance with repeated measures (alpha = .05) was conducted on each variable using SPSS v.12 (SPSS Inc., Chicago, IL). The appropriate assumptions for both within and between subjects ANOVA were considered. Simple effects were then analyzed with adjustments for multiple comparisons (.05/16 = alpha = .0032). If the three-way interaction was not significantly different, then two-way interactions were analyzed and the appropriate simple effects were analyzed with appropriate alpha level adjustments. If the two-way interactions were not significantly different, then single main effects were analyzed.

As indicated in the results section, while the results of the three-way ANOVA were noteworthy (thus included in this manuscript) they were unable to answer our root question about the difference in group performance under each task and how that changes as recovery progresses. Therefore, subsequent group*task ANOVAs with Bonferroni pairwise comparisons were conducted on each day for each variable. By doing this we hoped to remove what seemed to be a large effect due to testing time.

Results

*Three-way ANOVA (group*day*task)*

No three-way interactions were observed. The sagittal plane angular range of motion (SR; Table 4.1) was effected by a day*task interaction ($F = 3.269$, $p = .011$). SR significantly increased with time in each of the tasks a little differently. SR was greater after testing session 1 and greater during session 4 as compared to session 2 for the LEVEL ($p < .001$ and $p = .001$, respectively) and D-OB tasks ($p < .001$ and $p = .001$, respectively). SR was greater after session 1 for obstacle-crossing ($p < .001$). SR increased for each testing session of the Q&A task except between sessions 2 and 3 ($p < .001$).

Sagittal plane COM motion during each particular day tended to be increased during obstacle crossing tasks. During testing session 1, SR was lowest during the Q&A

task ($p = .001$), increased for the LEVEL task ($p = .001$), and was greatest for both the obstacle crossing tasks ($p < .001$). During session 2, all tasks were different with a similar trend as session 1 except that SR for single task obstacle crossing was greater than dual task obstacle crossing ($p = .005$). During session 3 and 4, SR was greater for both obstacle crossing tasks compared to both level walking tasks ($p < .001$).

Anterior peak CoM velocity (SV; Table 4.2) had both a day*task interaction ($F = 4.966$, $p < .001$) and a task*group interaction ($F = 4.144$, $p = .016$). There were no group differences for any individual task, but there were unique task differences for each group. Anterior velocity was significantly slower for dual task conditions as opposed to single task conditions in the control group ($p < .001$). Velocity in the concussed group increased as task difficulty decreased. The slowest velocity was experienced during D-OB, then during Q&A, OB and LEVEL respectively ($p \leq .008$).

Peak forward velocity of the CoM increased with each testing session and decreased with task challenge. After testing session 1 peak anterior velocity increased during LEVEL ($p < .001$) and OB ($p < .001$). For the Q&A task peak velocity was greater after session 1 ($p < .001$) and then was greater again after session 2 ($p \leq .004$). Velocity increased between each testing session for D-OB ($p \leq .005$) except between sessions 2 and 3. Anterior velocity was slower for dual task paradigms vs. single task paradigms during the first session ($p < .001$). During sessions 2 ($p \leq .004$) and 4 ($p \leq .001$) velocity was different between all tasks except Q&A and D-OB. During session 3 velocities decreased with increasing task difficulty ($p \leq .004$).

The frontal plane angular range of motion (FR; Table 4.1) had both task effects (F = 3.912, p = .019) and a group*day interaction (F = 4.484, p = .013). FR was greater for the Q&A task compared to the LEVEL (p = .005). Both groups had similar FRs until the last testing session, when the concussed group has a smaller frontal plane angular range of motion (p = .010). While there were no changes in control subject's performance over time, the concussed group had a decrease in frontal CoM motion from session 1 to 4 (p = .009).

Table 4.1. Mean values and standard deviations of COM angular ranges of motion.

Variable	**Task**	**Group**	**Time (days)**			
			2	**6**	**14**	**28**
SR (deg)	LEVEL	mTBI	23.9 (4.4)	25.8 (3.5)	25.9 (3.4)	26.3 (3.7)
		Cont.	24.6 (3.8)	25.9 (3.7)	26.4 (3.5)	27.0 (4.0)
	OB	mTBI	27.9 (3.3)	29.4 (3.3)	29.6 (3.2)	29.6 (3.5)
		Cont.	29.3 (3.4)	30.1 (3.6)	30.3 (3.4)	30.2 (3.5)
	Q&A	mTBI	22.6 (4.7)	24.7 (3.7)	25.2 (3.5)	26.0 (3.5)
		Cont.	24.0 (3.6)	25.5 (4.2)	25.8 (4.2)	26.2 (4.2)
	D-OB	mTBI	27.2 (3.1)	28.5 (3.7)	29.0 (3.1)	29.5 (3.4)
		Cont.	28.8 (3.7)	29.5 (3.8)	29.9 (3.9)	30.2 (3.6)
FR (deg)	LEVEL	mTBI	8.05 (2.1)	7.62 (1.6)	7.40 (1.6)	7.22 (1.8)
		Cont.	7.76 (1.1)	7.99 (1.5)	8.26 (1.7)	8.05 (2.1)
	OB	mTBI	7.63 (1.7)	7.52 (2.0)	7.39 (2.1)	6.86 (1.6)
		Cont.	7.92 (1.4)	7.67 (1.6)	8.23 (2.2)	8.30 (2.5)
	Q&A	mTBI	8.16 (2.0)	8.00 (1.8)	7.60 (1.7)	7.29 (1.5)
		Cont.	8.23 (1.6)	8.24 (1.7)	8.52 (1.5)	8.46 (2.2)
	D-OB	mTBI	8.30 (1.7)	7.57 (1.9)	7.42 (1.7)	7.05 (1.7)
		Cont.	8.09 (1.5)	8.04 (1.8)	8.49 (2.4)	8.53 (2.3)

Peak frontal plane CoM velocities (FV; Table 4.2) were significantly different for all tasks (F = 111.891, p < .001). The greatest velocity was experienced during D-OB, then OB, Q&A and LEVEL respectively.

There were no significant effects for the correct response percentage (P; Table 4.3). Day effects were observed for the number of answers correct (F = 5.025, p = .004) and the number attempted (F = 10.993, p < .001). The number of correct responses (C; Table 4.3) and the number of answers attempted (A; Table 4.3) were greater during the first testing session than during session 4. More answers were also attempted during dual task level walking compared to dual task obstacle crossing (t = 7.881, p = .007).

Table 4.2. Mean values and standard deviations of COM peak velocities.

Variable	**Task**	**Group**	**Time (days)**			
			2	**6**	**14**	**28**
SV (m/s)	LEVEL	mTBI	1.39 (0.14)	1.49 (0.14)	1.50 (0.15)	1.51 (0.15)
		Cont.	1.43 (0.17)	1.49 (0.17)	1.50 (0.16)	1.51 (0.17)
	OB	mTBI	1.35 (0.14)	1.44 (0.16)	1.44 (0.16)	1.46 (0.16)
		Cont.	1.42 (0.18)	1.48 (0.18)	1.47 (0.17)	1.49 (0.18)
	Q&A	mTBI	1.24 (0.17)	1.37 (0.17)	1.41 (0.15)	1.42 (0.17)
		Cont.	1.33 (0.17)	1.41 (0.19)	1.44 (0.20)	1.45 (0.20)
	D-OB	mTBI	1.24 (0.15)	1.33 (0.19)	1.37 (0.17)	1.39 (0.17)
		Cont.	1.33 (0.18)	1.41 (0.20)	1.42 (0.19)	1.45 (0.19)
FV (m/s)	LEVEL	mTBI	0.135 (0.036)	0.133 (0.035)	0.134 (0.030)	0.132 (0.030)
		Cont.	0.136 (0.025)	0.144 (0.030)	0.141 (0.028)	0.138 (0.030)
	OB	mTBI	0.159 (0.028)	0.153 (0.037)	0.146 (0.028)	0.148 (0.029)
		Cont.	0.161 (0.034)	0.162 (0.034)	0.165 (0.038)	0.167 (0.044)
	Q&A	mTBI	0.147 (0.037)	0.148 (0.038)	0.144 (0.031)	0.148 (0.033)
		Cont.	0.152 (0.030)	0.154 (0.031)	0.152 (0.030)	0.150 (0.038)
	D-OB	mTBI	0.176 (0.039)	0.173 (0.038)	0.167 (0.035)	0.168 (0.034)
		Cont.	0.177 (0.036)	0.175 (0.040)	0.174 (0.035)	0.176 (0.039)

Table 4.3. Mean values and standard deviations of secondary Q&A variables.

Variable	Task	Group	Time (days)			
			2	6	14	28
P (%)	Q&A	mTBI	.930 (0.13)	.922 (0.10)	.917 (0.12)	.939 (0.10)
		Cont.	.946 (0.07)	.912 (0.10)	.930 (0.11)	.937 (0.07)
	D-OB	mTBI	.915 (0.10)	.897 (0.10)	.947 (0.08)	.942 (0.08)
		Cont.	.922 (0.11)	.924 (0.10)	.936 (0.11)	.959 (0.10)
C (#)	Q&A	mTBI	4.15 (0.82)	3.86 (0.78)	3.87 (0.82)	3.78 (0.78)
		Cont.	4.16 (0.74)	3.84 (0.83)	3.82 (0.66)	3.74 (0.63)
	D-OB	mTBI	3.89 (0.68)	3.79 (0.69)	3.77 (0.60)	3.69 (0.73)
		Cont.	3.91 (0.77)	3.90 (0.68)	3.69 (0.78)	3.93 (0.68)
A (#)	Q&A	mTBI	4.42 (0.58)	4.09 (0.69)	4.09 (0.62)	3.92 (0.64)
		Cont.	4.35 (0.55)	4.13 (0.74)	4.10 (0.62)	3.94 (0.61)
	D-OB	mTBI	4.16 (0.51)	4.08 (0.60)	3.90 (0.54)	3.83 (0.71)
		Cont.	4.15 (0.67)	4.14 (0.64)	3.90 (0.76)	4.04 (0.61)

Crossing heights of both the trailing foot (TC; Table 4.4) and leading foot (LC; Table 4.4) were significantly affected by the testing session (trailing crossing: F = 7.363, p < 001; leading crossing: F = 5.380, p = .001) and task (trailing crossing: t = 8.802, p = .004; leading crossing: t = 7.415, p = .009). Trailing foot crossing height was greater during the first testing session compared to all others, and greater during dual task obstacle crossing. Lead foot crossing height was greater during session 1 compared to sessions 3 (p = .010), and also greater during dual task obstacle crossing (p = .009).

*Two-way ANOVA (group*task)*

Group*task interactions on specific days were significant for peak sagittal CoM velocity, but since the day interaction was also significant, it is not statistically appropriate to discuss in this section.

Table 4.4. Mean values and standard deviations of secondary obstacle clearance variables.

Variable	Task	Group	Time (days)			
			2	6	14	28
TC (cm)	OB	mTBI	20.4 (6.4)	18.5 (6.2)	18.2 (6.5)	18.4 (6.283)
		Cont.	19.0 (4.9)	17.4 (5.4)	18.4 (5.5)	17.5 (5.8)
	D-OB	mTBI	21.9 (6.0)	19.3 (5.5)	19.1 (6.4)	19.2 (6.8)
		Cont.	20.0 (4.8)	18.9 (5.9)	19.2 (6.4)	18.7 (5.7)
LC (cm)	OB	mTBI	15.6 (3.4)	15.5 (3.0)	14.7 (3.6)	15.5 (3.5)
		Cont.	16.0 (3.8)	14.8 (3.0)	15.1 (2.8)	14.8 (3.1)
	D-OB	mTBI	17.3 (4.4)	15.8 (3.6)	15.1 (3.7)	15.8 (3.5)
		Cont.	16.5 (2.8)	15.3 (3.3)	15.7 (3.7)	15.8 (3.3)

Frontal plane peak velocities only displayed a group*task interaction during the 4th testing session (F = 3.239, p = .024). There was a trend for concussed subjects to have a slower velocity during obstacle crossing (p = .051). Task comparisons within each group indicate that single task obstacle crossing performance as the main significant difference between the two groups. Control individuals had significantly slower medial velocities during LEVEL compared to all other tasks ($p \leq .018$) and had slower velocities during Q&A compared to both obstacle crossing conditions ($p < .001$). Concussed individuals had slower velocities during LEVEL compared to all other tasks ($p \leq .005$), but both Q&A and OB velocities were slower than D-OB ($p < .001$).

Discussion

The purpose of this study was to examine gait stability and secondary task performance as task difficulty increases in the cognitive domain, motor domain, or both as performed by healthy individuals and those suffering from concussion. The overall goal was to find a gait task that discriminates the effects of a concussion and monitor performance with it at different points during recovery.

Initially, all subjects walked a bit more conservatively, but at subsequent testing sessions larger angular ranges of motion and faster peak velocities in the sagittal plane were adopted for each of the tasks. Notably, there were gradual increases in liberal walking patterns across testing sessions, except for the single task obstacle crossing condition. After the first testing session there were no longer any statistically significant differences in sagittal peak velocities or angular ranges of motion during OB trials. A major limitation in our study was the change in performance for control individuals over testing periods. All else being equal, control performance should not change over time suggesting that more practice trials may have been needed before each testing session. This limitation in our protocol was actually insightful in one regard: whereas performance during other tasks changed over time, performance during single task obstacle crossing seemed to remain stable for each testing session after the first, indicating its resilience to practice effects compared to the other tasks we used.

Sagittal plane range of motion was equivalent between similar types of motor tasks. Both obstacle conditions resulted in larger CoM motions than the level walking conditions. This seemed to be a result of the physical nature of the obstacle, requiring longer step lengths to clear the barrier. As step length increases so does the angle between the CoM to CoP and the vertical projection up from the CoP. On the other hand, peak CoM velocities in the sagittal plane were similar between tasks with similar cognitive demands. This was indicative of conservative walking during attention dividing tasks as previously reported for both concussed [11, 70] and healthy individuals [87]. All individuals chose more conservative secondary task performance as task difficulty increased as well. Higher clearance heights over the obstacle were used when a cognitive task was simultaneously required and fewer answers were attempted in the question and answer task when obstacle crossing was simultaneously performed.

The only difference in sagittal plane motion between the two groups, which varied by task, was for anterior peak velocity. Controls walked slower during attention dividing tasks than during single tasks. Concussed individuals showed a similar pattern but actually walked slower as challenge increased between each task. They slowed down when either an obstacle or a secondary task was added to the protocol; and slowed even further when both were performed simultaneously.

While sagittal plane motion of the CoM is useful in measuring the conservative approach to walking that individuals use, frontal plane CoM motion is understood to be a better predictor of gait stability [18, 88]. Larger CoM displacements in the frontal plane indicate that all individuals experience decreased balance control during the Q&A task compared to single task conditions. Surprisingly, there was not a difference in CoM displacement during divided attention obstacle crossing compared to the other easier tasks. Performing obstacle crossing with a cognitive secondary task appeared to shift the priority of the individual towards maintaining stability, resulting in improved balance control as opposed to situations with a cognitive task but without an obstacle condition. The shift towards prioritizing stability is further indicated by fewer secondary answers attempted in the D-OB task compared to the Q&A task. While this does not refute the hypothesis that a ceiling effect in gait stability exists as task challenge increases, it indicates that the tasks chosen in this study are not appropriate for answering this question. Rather than combining an increase in cognitive challenge with an increase in motor challenge, increasing the challenge in either individual domain might be more appropriate at determining if and when a ceiling effect in stability occurs.

Faster CoM velocity in the frontal plane for the obstacle crossing tasks may initially seem to contradict the Q&A task as most destabilizing, but we believe this variable is offering a different view of the situation. CoM range of motion is measured over the stride, but peak velocity was at one instant during the stride. Increased peak velocity due to obstacle crossing seems to be a result of the physical nature of crossing over an obstacle. After the foot is lifted higher to avoid an obstacle the body has more time to accelerate before the foot hits the ground, thus increasing the peak velocity of the individual under these conditions. The fact that peak velocity also increased from single to dual task indicates that the Q&A task is more destabilizing.

While the Q&A task seems to be more destabilizing, the follow-up 2-way analysis indicates single task obstacle crossing as best to distinguish a possible recovery of balance control by concussed individuals. The only significant interaction for frontal peak velocity was found during the 4th testing session. The fastest peak velocities that healthy individuals experienced were during both obstacle crossing conditions. On the other hand, concussed individuals displayed significantly slower velocities during single task obstacle crossing compared to dual task obstacle crossing. This, in combination with the only evident difference between the two groups for a particular task being during single task obstacle crossing, indicates that this task is performed more conservatively by concussed individuals after a month post-injury compared to control individuals. It is our contention that concussed individuals only perform this task more conservatively 28 days after their injury because the underlying mechanisms for frontal plane CoM control are reacquired by this time. The possible mechanisms that could account for this include improved perception of the environment [89], increased strength [90], improved coordination [91] or some combination of these recovered motor abilities compared to immediately after the concussion.

Conclusions

Sagittal plane CoM variables and secondary task variables indicate that all individuals adopt conservative gait strategies when posed with increasingly difficult tasks. The manner in which gait is altered varies depending on the perturbation posed to the individual. When both cognitive and motor difficulty increase concussed individuals were still adopting a more conservative gait strategy, indicating that a ceiling effect is at least not applied to safer gait adaptations for the utilized tasks. These tasks were also unable to identify any ceiling effects in gait stability in the front plane, since neither task of increased challenge compared to level walking resulted in similar destabilizing effects. The only possible evidence of a ceiling effect in performance was discovered in the secondary measures of cognition and obstacle clearance; both indicating decreased performance in the most challenging task.

The results of this study indicate that a divided attention task can result in the most instability during gait. However, all individuals may be subjected to this instability.

An obstacle crossing task was actually better at distinguishing a recovery of motor function acquired by concussed individuals (similar to findings of the previous study), which might also indicate that obstacle crossing tasks might be an appropriate method for testing the motor function of concussed individuals prior to a return to normal activities.

Bridge

While this study failed to produce any significant results beyond those found in the first study, it did show that combined motor and cognitive increased perturbations do not create a ceiling effect in gait performance. Rather they challenge individuals in very different ways. This has raised more questions about ceiling effects. I certainly still believe ceiling effects exist, but now we must consider multiple ceiling effects. We cannot just assume a ceiling effect on general performance. Each type of perturbation probably has its own ceiling as challenge is increased. The findings from this study show that the interaction between gait (particularly obstacle crossing gait) and attention needs to be investigated further. This is what we proposed to do in the third study of this dissertation. In the next study I also begin the process of picking attention apart to understand which components of attention interact with gait performance following a concussion.

CHAPTER V

SPATIAL ORIENTATION OF ATTENTION AND OBSTACLE AVOIDANCE FOLLOWING A CONCUSSION

Introduction

Recent studies have predicted an accumulation of damage and severity from concussions if a patient incurs a subsequent injury while still suffering from symptoms of the previous injury [57, 92, 93]. Safety during motor tasks is imperative to decreasing the likelihood of permanent brain damage following concussion. While active external sources of injury (biomechanical forces caused by animate objects or persons) can rarely be predicted and avoided, passive sources of injury (inanimate objects causing a trip and fall) might be avoided assuming the appropriate neural pathways are functioning properly. Examinations of obstacle crossing performance during gait and the particular involvement of attention required of this motor task are of particular importance so that subsequent concussions may be reduced.

The spatial orientation of attention is required in daily activities when one must process visual information associated with objects within the field of view [94]. Previous reports have indicated that the ability to orient attention as measured using the Attentional Network Test (ANT) [23] is deficient immediately following a concussion, but returns to normal within a week post-injury [20, 36]. This orienting component of the attentional network test (ANT) evaluates the ability of the participant to make covert shifts of attentional resources to the cued spatial location, which in turn leads to quicker processing of the subsequent target appearing at that location [20]. More severely injured patients also have demonstrated diminished spatial attention after a year post-TBI [44].

Obstacle avoidance during gait is a daily activity that appears to be adaptively altered following TBI. Severe TBI patients have been shown to display dynamic imbalance with increased medial-lateral center of mass motion while crossing an obstacle during walking [18]. Others have concluded a conservative adaptation to brain injury at the same time. One report found that severe TBI patients walk slower and lift their foot higher to safely avoid obstacles during walking [35], as do mildly concussed individuals in a separate report [11].

To what extent are these attention and gait deficits following concussion related to each other? While there is no direct evidence available which addresses this issue, we have recently shown that gait instability following concussion is exaggerated when gait is performed in conjunction with an attentionally demanding secondary task [11, 19, 70, 76]. Moreover, recent studies have demonstrated that the ability to avoid obstacles, at least during reaching engages dorsal visual stream structures [10, 95]. Given that the dorsal visual stream terminates in the posterior parietal lobe, where spatial attention is at least partially achieved [9], one can speculate that deficits in the ability to spatially orient attention and avoid obstacles should co-vary. The aim of the current investigation, therefore, was to examine the relationship between obstacle avoidance during walking and the spatial orientation of attention following concussion. We predicted that participants with concussion who displayed the largest deficits in spatial attention would also have a tendency to exhibit a greater risk of tripping over the obstacle during walking. Information gathered in this study will show how a computer examination of attention is related to functional motor performance. This can then lead to a straight forward examination of motor performance in a clinical setting that can distinguish between concussed individuals that suffer motor deficits and those not at risk of hazardous environmental interactions.

Methods

Seventeen participants who suffered a grade 2 concussion (9 males, 8 females; mean age: 21 ± 1.72 years [age range: 18-24 years]; education: 13.4 ± 0.94 years; height: 178± 12.6 cm; mass: 88.8± 28.0 kg) were identified from within the University of Oregon student population. A majority of participants were associated with intercollegiate, club, or intramural sports, or recreational activities. All participants were initially recruited for testing within 2 days following the injury (mean elapsed time: 38 ± 11.6 hours; range: 12-50 hours) after identification by certified athletic trainers and/or attending medical doctors in the university intercollegiate athletic program or the student health center. Subsequent testing occurred 6, 14 and 28 days after the injury. The source of the injury ranged from impacts to the head occurring during sporting activities to accidental falls and collision with inanimate and/or stationary objects. The severity of the injury was categorized by the attending certified athletic trainers and/or medical doctors in accordance with the definitions originated by the American Academy of Neurology [73]. A Grade 2 was assigned if the participant remained disoriented for greater than 15 minutes, but did not lose consciousness for any period of time. None of the participants with concussion had a structural brain scan performed – thus, the extent of any abnormalities was unknown. However, previous brain imaging research has found structural abnormalities in only a small percentage of cases following concussion [96].

Age- (mean age: 21 ± 2.32 years [age range: 18-27]), gender- (9 males, 8 females), activity level- (e.g., football players were matched with teammates who played the same position), education level- (13.9 ± 2.00 years), height- (177± 12.0 cm) and mass- (85± 29.8 kg) matched control participants were recruited from within the same university population and tested at the same intervals. Individual control participants were paired with a matched participant with mTBI. All of the participants signed a consent form prior to partaking in the study and the local university human subject's compliance committee approved the experimental protocol.

Testing began with an analysis of obstacle crossing during walking. All participants were dressed in the same attire of a tank top and shorts without socks or shoes. A retro-reflective marker was placed on the dorsal surface of each foot between the 2nd and 3rd metatarsals so that the base of the markers resided just proximal to the metatarsophalangeal joints. Foot lengths between groups were equivalent (mTBI: 26.8±2.73 cm; Cont: 26.5±2.59 cm). Given the equivalent foot lengths and linear relationship to toe length [97], we assumed no group differences in marker location with respect to the end of the 2nd toe. Three dimensional marker trajectories were collected with an eight camera motion tracking system (MotionAnalysis Corp., Santa Rosa, CA) at a sampling frequency of 60 Hz. The cameras were positioned surrounding an eight-meter walkway. A PVC pipe (1/2” diameter, 1.3 m length) set atop two adjustable uprights halfway down the walkway was used as an obstacle. The obstacle was set to 10% of each subjects’ particular body height. A marker was placed at each end of the pipe. The obstacle was fashioned to easily fall if contacted rather than remaining stiff and causing a trip.

Several practice trials were allowed so that subjects could become accustomed to walking in the laboratory environment. Subjects were asked to walk at a comfortable self-selected pace. The obstacle crossing task was performed in two blocks of five trials. The first block only involved walking and crossing over the obstacle. In the second block of trials a divided attention task was completed during obstacle crossing. Subjects continuously responded to a question posed at the beginning of each trial. Questions included common tests from a clinical mental status examination: spelling a common five-letter word in reverse, continuous subtraction by a certain number, and reciting the months of the year in reverse order [75]. At the beginning of each trial the subject was given the specific task for that trial (e.g. “count backwards by sevens starting at ninety-three”). The subject then started walking and answering at the same time and stopped answering at the end of the walkway. Each walking trial lasted approximately 6 seconds. The subject then returned to the starting position and waited several seconds for the next trial to begin. Subjects rested for several minutes between trial blocks. In total, the obstacle crossing portion of the data collections lasted approximately 20 minutes.

Following motion analysis testing, participants performed the Attentional Network Test (ANT) that was designed by Fan and colleagues [23] for the purpose of assessing the three major components of visuospatial attention; alerting, orienting and conflict resolution. Throughout each testing session, participants were seated ~50 cm in front of a computer monitor. Subjects were presented with visual targets subtending ~1° of visual angle to which they responded. Figure 5.1A illustrates the basic characteristics of a representative trial. At the onset of each trial a central fixation crosshair was displayed. On 75% of the trials a precue (asterisk) was displayed briefly (100 ms) after a variable delay (400-1600 ms). Conversely, on the remaining trials no precue was presented. After a fixed delay (400 ms) a target arrow pointing to the left or right was displayed either 5 deg above or below the central fixation crosshair. Participants were instructed to press the left or right mouse button corresponding to the direction of the target arrow as quickly and accurately as possible. The target arrow disappeared when either the subject responded or after 1700 ms, whichever occurred first.

The precue could appear in one of three configurations (Figure 5.1B). Trials with a spatially informative precue were characterized by the appearance of the asterisks at the location where the subsequent target arrow would appear. These 'spatial precue' trials were always valid since the precue never appeared at a location at which the target did not subsequently appear. In trials containing a 'double precue', two asterisks were displayed 5° above and 5° below the central fixation crosshairs. During trials incorporating a 'central precue', the asterisk was presented at the same location as the central fixation point. In conjunction with these precue arrangements, the target arrow likewise was displayed in one of the three configurations (Figure 5.1C). The target arrow could be displayed alone ('neutral' trials) or flanked on either side by a total of four arrows of the same size (two to the left and two to the right). During trials with flanker arrows, the arrows could be 'congruent', where flanker arrows pointed in the same direction as the target arrow, or 'incongruent' where the flanker arrows pointed in the opposite direction to the target arrow. The three different target types were equally distributed in trials containing each of the different precue conditions.

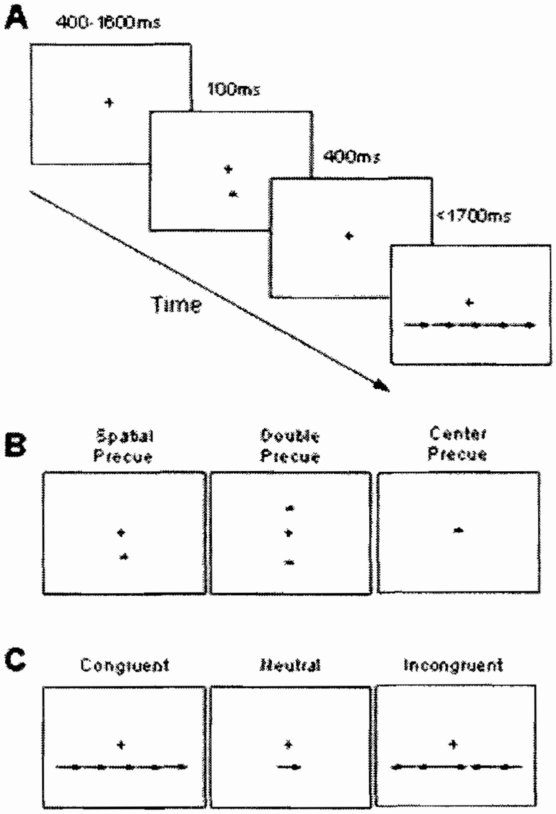

Figure 5.1. Events occurring during the trials. (**A**) Sequence of events in a typical trial. *Plus sign*, fixation cross; *asterisk*, precue; *arrows*, target. Participants responded to the appearance of the target arrow by pressing the corresponding button on the mouse. In this example, the right mouse button would be pressed. (**B**) Precue configurations. *Left*, spatially informative precue; *middle* and *right*, spatially uninformative precues. On some trials, no precue was given. (**C**) Target configurations. *Left*, congruent targets; *middle*, neutral target; *right*, incongruent targets.

All participants completed a series of 24 practice trials with visual feedback concerning reaction time and accuracy prior to data collection. The entire ANT testing consisted of 3 blocks of experimental trials comprised of 96 trials each (4 cue conditions x 2 target locations x 2 target directions x 3 flanker conditions x 2 trials). Experimental trials were pseudo-randomized and contained no visual feedback.

Motion data was filtered with a low-pass Butterworth filter at 8 Hz. The primary dependent variables of interest for obstacle crossing were vertical clearance heights of each marker over the obstacle. These were measured as the vertical displacement between a point in the middle of the obstacle and the marker of the respective foot at either the frame before or after obstacle crossing; whichever was closer to the obstacle in the anterior/posterior direction (Figure 5.2).

The primary dependent variable of interest for the ANT was the median reaction time on accurate trials. The alerting effect was evaluated by subtracting the median reaction time during double precue trials from the median reaction times on no precue trials, regardless of the target configuration. This subtraction represents the benefit in reaction time associated with knowing the target would appear exactly 400 ms later. The orienting effect was calculated by taking into account median reaction times in trials with the spatial precue. Although this precue communicates when the target arrow will appear, it also indicates the exact location where the target will be displayed. Therefore, the orienting effect was evaluated by calculating the difference between the median reaction times of center precue trials and the median reaction time of spatial precue trials. Trials containing either the center or spatial precues alert the subject to the appearance of the

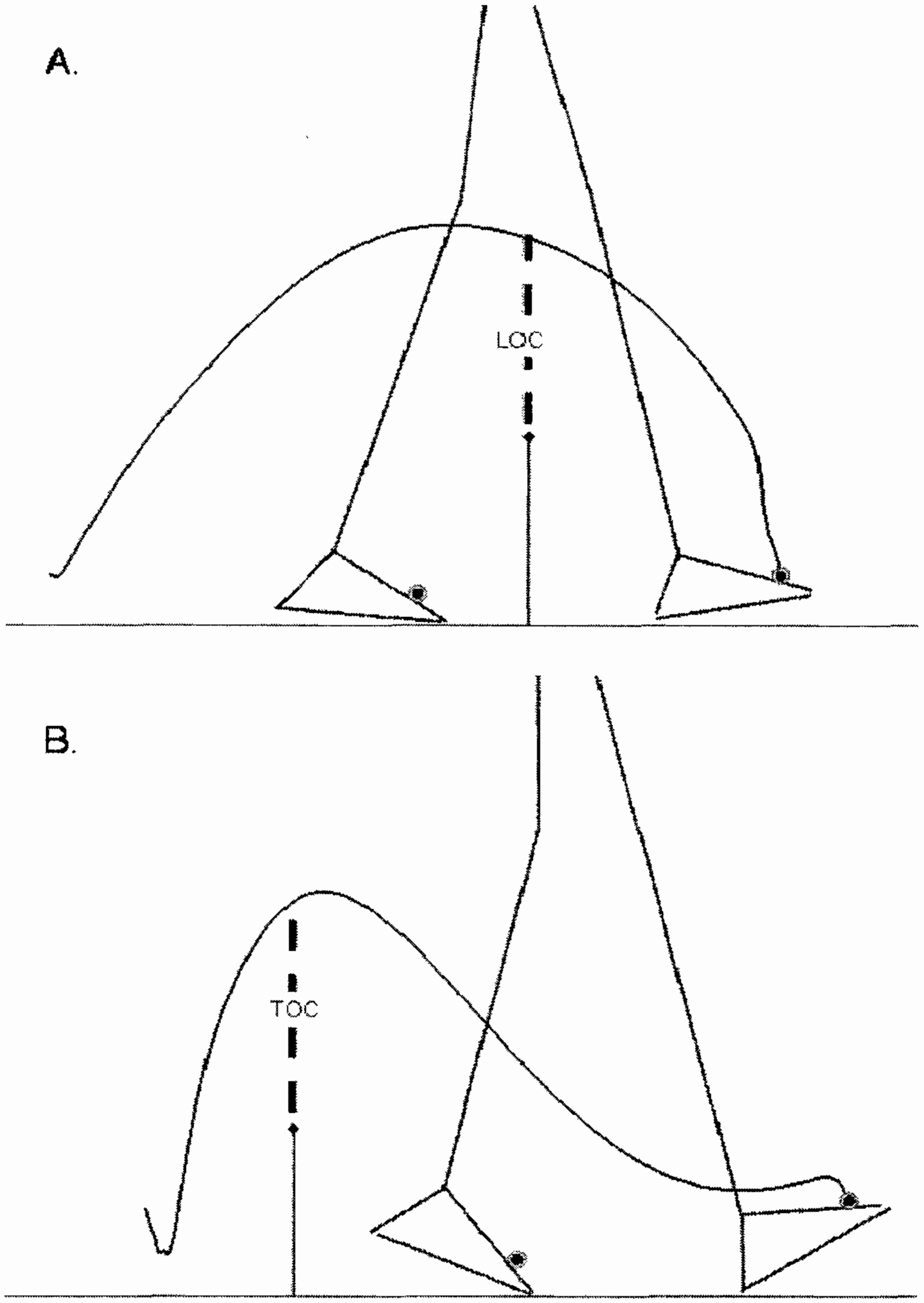

Figure 5.2. Typical toe marker trajectories in the sagittal plane when stepping over an obstacle with the leading (**A**) and trailing (**B**) feet. LOC is the lead foot obstacle clearance measurement. TOC is the trailing foot obstacle clearance measurement.

subsequent target. Therefore, the subtraction of the reaction times from these conditions represents the decrease in reaction time associated with awareness of the precise location at which the subsequent target would be presented. The conflict effect, employed to appraise the executive component of attention, involves calculating the difference between the median reaction time for responses to congruent versus incongruent targets. This calculation determines the influence of facilitating or distracting information on reaction time, respectively.

All trials which resulted in an obstacle contact were excluded from analysis. Analyses of variance (ANOVA) were performed to investigate the differences within each attentional component across the various conditions and within the two obstacle-crossing tasks (means and mean inter-trial coefficients of variation). Specifically, 2 (subject group) x 4 (testing day) mixed model ANOVAs were performed to assess the differences between groups and across testing days. A post-hoc adjusted test was used to examine group differences within a testing day if overall comparisons were significant. We also performed linear regressions between obstacle clearance and the alerting, orienting and conflict effects on each group, day and task. P-values were set to 0.05 to indicate statistical significance.

Results

There were no significant mean differences in obstacle crossing parameters for either single or dual task situations between the two groups or over the four testing periods. Group by day comparisons of TOC and LOC in the single and dual task situations consistently had p-values above 0.2, indicating that even trends in statistical significance in these group-generalizing comparisons were weak. Because the statistical insignificance of these parameters is still important for understanding how our group of individuals compares to other samples of concussed individuals we have included group, task and day performance values in Table 5.1. We did notice statistically more variability between trials in lead foot crossing height by concussed individuals compared to control individuals during dual-task obstacle crossing (F = 2.901, p = 0.039; Table 5.2). This difference was specifically at the 28 day testing between the two groups (p = 0.012).

Table 5.1. Mean performance values of obstacle clearance height of the lead foot (LOC) and trailing foot (TOC) for each group, over each day, during each task.

			Testing day			
Variable	Task	Group	2 days	6 days	14 days	28 days
TOC	Single	mTBI	18.6	17.1	17.7	17.8
		Cont.	19.8	18.7	19.8	19.6
	Dual	mTBI	20.6	18.7	18.8	18.0
		Cont.	20.0	19.3	21.0	20.4
LOC	Single	mTBI	15.3	15.5	14.9	15.7
		Cont.	15.5	14.7	15.1	15.3
	Dual	mTBI	16.8	15.8	14.6	15.8
		Cont.	15.7	14.8	15.5	15.7

Since our group of participants are a subset from a previously published article, the results of our analysis of variance on attention have been previously reported with a larger sample size [20]. Even with three fewer subjects in each group we still found a similar group by day interaction in the spatial orientation of attention (F = 4.89, p = .0065). An mTBI resulted in a larger effect size than controls within 48 hours post-injury (p = .0004). However, by one week there were no longer group differences for this variable. By contrast, there were no group differences for conflict resolution or the alerting component of attention.

Table 5.2. Mean coefficients of variation of obstacle clearance height of the lead foot (LOC) and trailing foot (TOC) for each group, over each day, during each task. Statistically different values are outlined.

			Testing day			
Variable	Task	Group	2 days	6 days	14 days	28 days
TOC	Single	mTBI	0.123	0.139	0.166	0.126
		Cont.	0.121	0.118	0.113	0.132
	Dual	mTBI	0.128	0.140	0.140	0.143
		Cont.	0.144	0.138	0.139	0.097
LOC	Single	mTBI	0.112	0.121	0.123	0.095
		Cont.	0.107	0.127	0.078	0.082
	Dual	mTBI	0.128	0.139	0.120	0.158
		Cont.	0.141	0.105	0.132	0.095

The subject specific linear regressions conducted for each group on each day resulted in significant relationships between spatial orientation of attention effect size and obstacle clearance heights, but only within the mTBI group. During single task obstacle crossing the mTBI group showed significant negative correlations between orienting effect size and lead foot obstacle clearance. The relationship shows that participants with mTBI who had a reduced ability to orient attention in space (higher spatial effect size) also tended to cross the obstacle with lower lead foot clearance. Likewise, in participants with mTBI in which the spatial orientation of attention was relatively unaffected, lead foot obstacle clearance tended to be higher. On the initial testing day (Figure 5.3) immediately after the injury this relationship was the highest at 29% explained variance ($R^2 = .294$, $p = .037$), with gradually decreasing correlation values as recovery progressed (Figure 5.4).

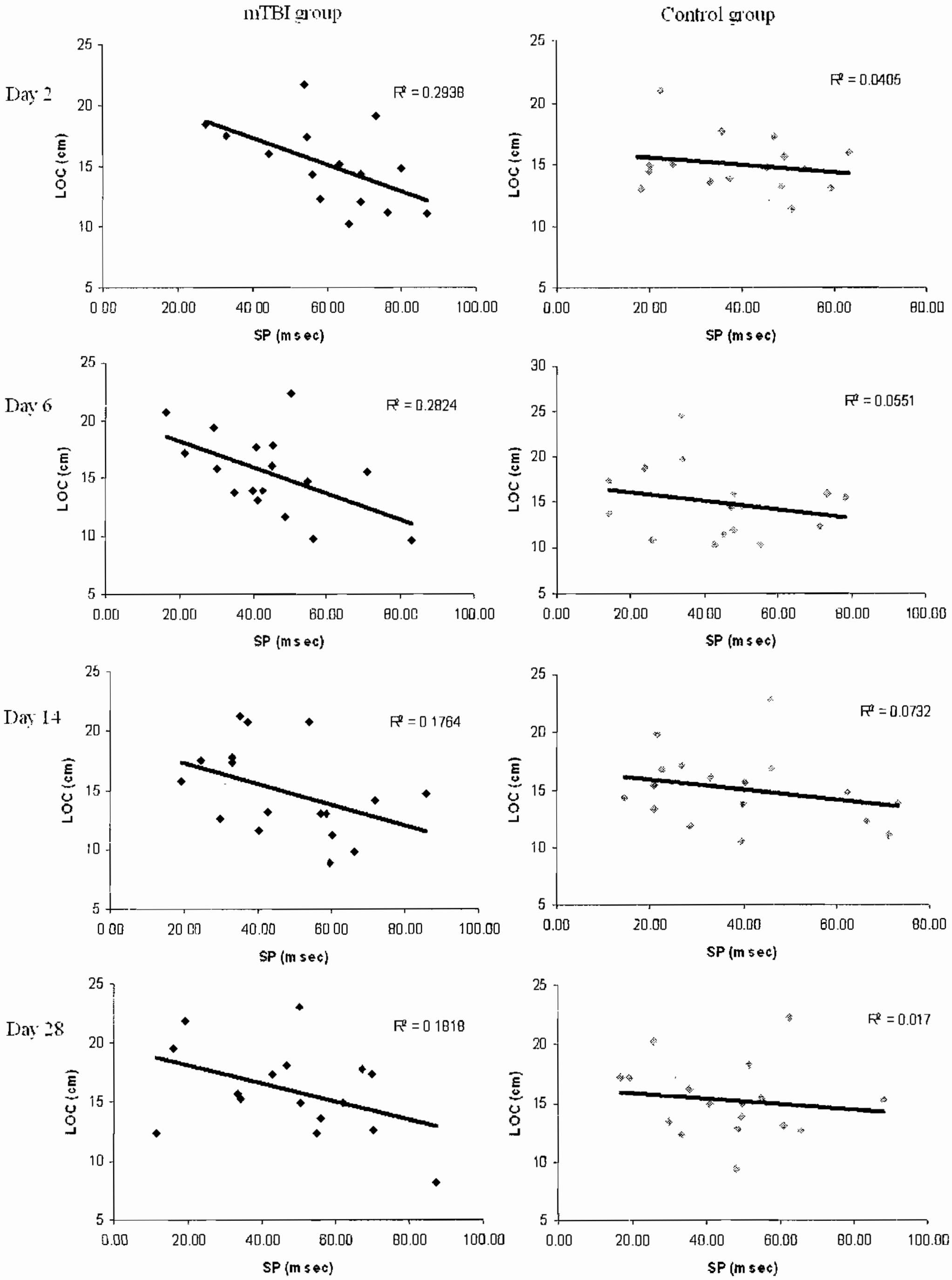

Figure 5.3. Regression plots of spatial orienting effect size (SP) vs. lead obstacle clearance (LOC) during single task walking for each group on each day. The left graphs with black symbols indicate the regression lines for mTBI participants. The right graphs with gray symbols indicate the regression lines for control participants. Testing days are sequential in rows.

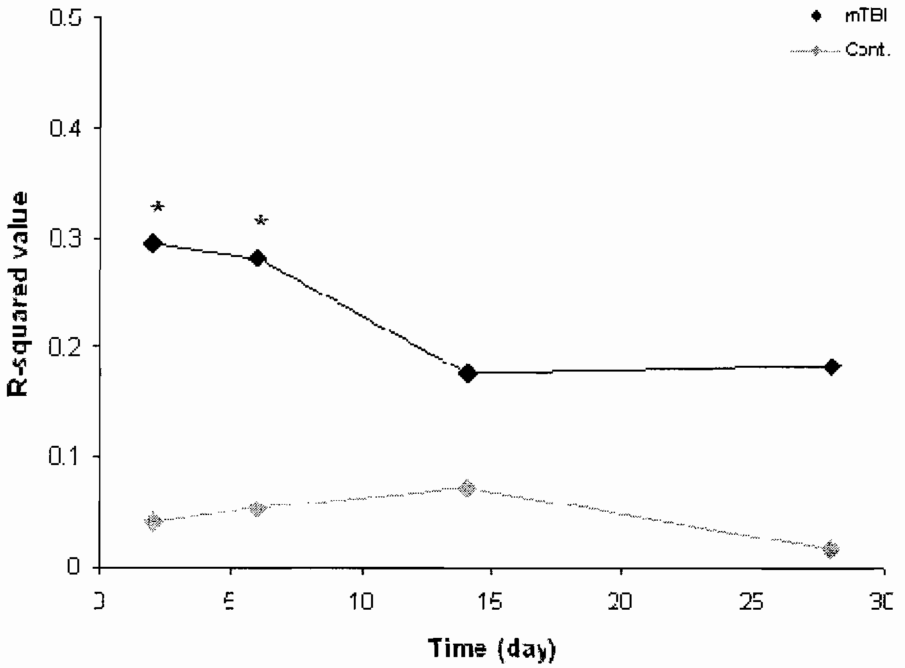

Figure 5.4. R^2 values for linear regressions performed between spatial orientation of attention effect size and lead foot obstacle clearance during single task obstacle crossing. MTBI participants are black symbols. Control participants are gray symbols. *Asterisk*: significant correlation ($p<.05$).

When the obstacle crossing gait task was performed in conjunction with an attention demanding secondary task, the same relationships between the orienting effect and both the lead (Figure 5.5) and trailing (Figure 5.6) foot clearances were observed within the mTBI group. Within 48 hours of the injury this relationship for lead foot clearance had nearly 48% explained variance ($R^2 = .477$, $p = .004$); whereas the trailing foot obstacle clearance shared 26.5% of its variance with the spatial orientation effect size ($R^2 = .265$, $p = .050$). On subsequent testing days these relationship gradually returned to control values. Once again there were no significant relationships within the control group.

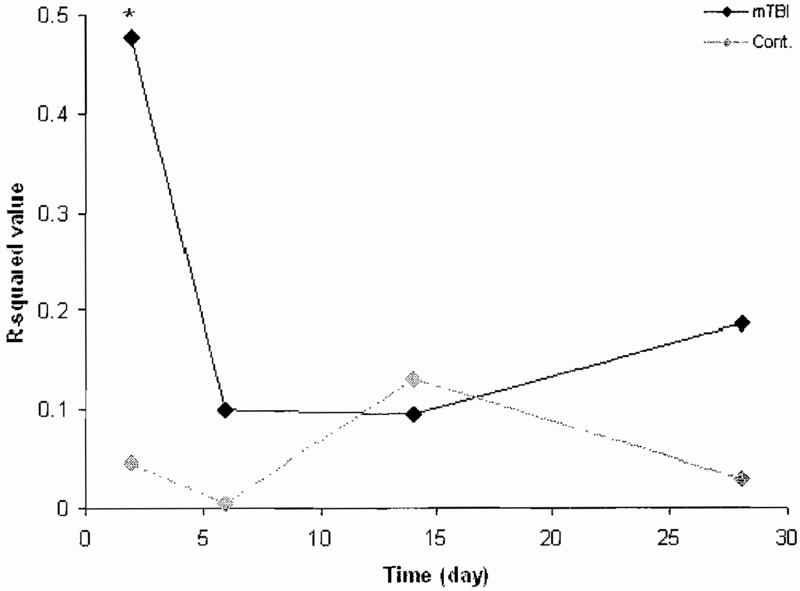

Figure 5.5. R^2 values for linear regressions performed between spatial orientation of attention effect size and lead foot obstacle clearance during dual task obstacle crossing. mTBI participants are black symbols. Control participants are gray symbols. *Asterisk*: significant correlation ($p<.05$).

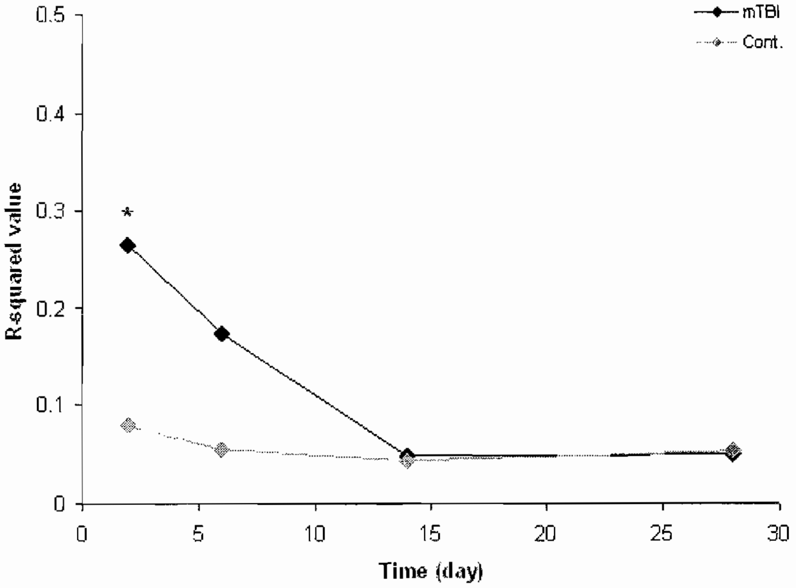

Figure 5.6. R^2 values for linear regressions performed between spatial orientation of attention effect size and trailing foot obstacle clearance during dual task obstacle crossing. mTBI participants are black symbols. Control participants are gray symbols. *Asterisk*: significant correlation ($p<.05$).

Conflict resolution showed no correlation to obstacle crossing for either single or dual task walking in either group. The alerting component of attention only showed a significant correlation to trailing toe clearance during dual-task walking in the mTBI group on the first testing day ($R^2 = .270$, $p = .039$).

Discussion

This current investigation examined the relationship between obstacle avoidance during walking and components of attention, specifically focusing on spatial orientation of attention in healthy college-aged individuals and those suffering from a concussion. In summary, the ability to orient attention was moderately correlated to lead foot obstacle clearance after a concussion, but not in healthy controls. When taxed with an attention dividing task during gait, the ability to orient attention was correlated even more with lead foot clearance and also moderately correlated to trailing foot clearance. The deficits in the ability to spatially orient attention observed in the participants with concussion improved to normal by 6 days post-injury and this coincided with decreased correlations between orienting attention and obstacle avoidance.

Previously, other researchers have found obstacle crossing differences long after brain injury [18, 35]. We found greater trial variability in foot crossing height by 28 days post injury similar to the increased variability that was observed by McFadyen et al. (2003). The difference we found in trial variability between concussed and controls at day 28 (but only for divided attention trials) seems to indicate that concussed individuals may not feel the same conservative strategies (increased attention paid towards the obstacle) utilized earlier in their injury were prudent at times during their final testing. This could prove dangerous for concussed individuals that may in fact still be susceptible to multiple concussions. Future examinations should test individuals longer after injury to uncover the importance of this increased variability in crossing performance.

Our previous reports also indicated group differences in conflict resolution and spatial orientation, but not alerting. With three fewer matched pairs in this study, we only observed trends of poor conflict resolution performance by concussed individuals, but our findings for spatial orientation and alerting were similar to those previously reported [20, 36]. Our previous research has indicated that participants with mTBI were able to use spatially informative precues to approach near normal reaction times in determining target direction. When precues were not available, however, reaction times were considerably slower [36]. A longitudinal analysis indicated that this deficit resolved within one week post-injury [20]. A subsequent study using the gap saccade paradigm indicated that this spatial orientation deficit was partially due to difficulties in appropriately disengaging attention from the point of central fixation [98].

Environmental obstacles encountered in a normal day include other people, furniture, stairs, street curbs, door thresholds and miscellaneous objects on the floor. Avoiding these obstacles requires an ability to precisely reassign attention to and from the obstacle before and during crossing. In fact, the requirement of attention during obstacle avoidance (while walking or with reaching tasks) has previously been alluded to [95] and demonstrated [67]. The prospect that the orienting component of attention is specifically involved in obstacle avoidance makes sense when one considers that obstacle avoidance has been shown to be a dorsal visual stream process with deep ties to areas surrounding the intraparietal sulcus [10, 95, 99, 100] and spatial orientation of attention has similar localization within the parietal cortex [7-9].

Obstacle avoidance studies focusing on reaching have hypothesized a minimum distance maintained between the hand and obstacles in the environment [10, 101]. Avoiding an obstacle during walking is even more important in most cases, as contact could result in a trip and fall. Increasing clearance height would be the safest approach to avoid contact. Our analysis was not originally designed to track obstacle contacts therefore we cannot speculate as to the number of contacts each particular subject had with the obstacle. We did notice however, that a majority of our concussed individuals did make contact with the obstacle at some point in their testing sessions, while control subjects rarely contacted the obstacle. Obstacle contact trials were not factored into our analyses.

The fact that we did not observe correlations between executive functioning and obstacle clearance contradicts recent finding that obstacle clearance is actually increased by more severely injured patients that perform poorly on executive function tests [102]. The major differences between this report and our experiment are that the previous study measured performance (1) long after (2) a severe brain injury and (3) they did not specifically analyze any other components of attention. The authors of this report conclude the more conservative locomotor performance is correlated with poor planning ability [102]. However our findings suggest just the opposite to be true immediately after a brain injury, before a possible adaptation to this injury has developed.

Interestingly, the correlations observed between obstacle avoidance variables and spatial attention effects only occurred in the mTBI group, whereas controls showed no such correlations. However, it seems unlikely that parietal lobe areas of the brain are engaged during obstacle avoidance only after a concussion. Rather, we hypothesize that the results are related to a decreased attentional capacity following a concussion [37]. Because of this, participants with a concussion may recruit attention-related structures in the dorsal pathway to a greater extent than normal, as has been demonstrated for structures in the frontal cortex during working memory tasks [103], such that when an additional secondary task is also included they become less able to appropriately orient their attention to the object and, thus, avoid it with lower, less safe clearances. Indeed, the even stronger correlations observed for lead and trailing foot clearances during the attention dividing task support this conjecture.

Reduced attentional capacity might then be considered to be the primary reason why concussed individuals show any correlation between spatial orientation and obstacle clearance, rather than spatial orientation as the primary influencing neural component. However, since we did not observe similar trends in correlations between conflict resolution or alertness with obstacle avoidance, our results support the primary involvement of spatial orientation in obstacle crossing. To further support our conclusion that the dual-task situation draws resources away from spatial orientation of attention to obstacle crossing following concussion we could have subjects perform a dual-task ANT paradigm and measure the effected reaction times. Unfortunately, this was not a part of our original experimental design and this information is not available in the literature for concussed individuals. Wijers and colleagues do however suggest that spatial orientation of attention is affected by divided attention situations [104]. Presumably, a group with diminished ability in divided attention situations (as some mTBI subjects) would have increased challenge to spatial orient attention appropriately.

We might also point out that within the concussed group not everyone displayed similar crossing strategies. Some of the individuals increased their crossing height while others had a decreased crossing height compared to control individuals. This is shown by the insignificant mean crossing height analysis and a visual inspection of the spread in obstacle clearance heights. This supports our notion that generalizing all brain injured individuals into one group can be problematic. If we were to purely rely on group information then we might have assumed that concussed individuals crossed over obstacles similar to healthy individuals. However, our regression analysis in this study points to the fact that concussed individuals must be considered on a case-by-case basis when at least considering obstacle crossing. Only individuals that had poor spatial orientation of attention had lower crossing heights, while intact spatial orientation led to higher crossing heights following concussion. This information is even more important for clinicians, as they are relied upon to provide sound advice for a normal return to activity. If the clinician relied solely on generalized data to determine the health of a specific individual, that individual may be placed in greater risk of re-injury. Currently, motor task performance is not a standard procedure in determination of health following concussion.

We suspect that correlations to trailing foot clearance for spatial orientation and alertness only became significant during the dual task situation because of the purely feed-forward information (independent of lead foot trajectories) used in appropriately crossing with the trailing foot [105]. Information for crossing this foot presumably comes from on-line use of the representation of the obstacle's stature and planning of the crossing technique. Planning is said to occur at least two steps prior to the obstacle [106]. At this time, subjects in our study were already responding to a secondary task that engaged resources normally used for processing information concerning obstacle dimensions, thus interfering with the appropriate planning for avoidance by the concussed group.

Still unexplained from our results is the remaining variance between orientation of attention and obstacle clearance. A limited attentional capacity requirement prior to seeing significant correlations in these variables partially explains the remaining variance. If attentional capacity was unaffected in a few of the concussed participants then those individuals would tend to decrease the correlations observed. We must also consider natural human variation when considering the observed correlations. Also undetermined with the current protocol is which component of orienting attention particularly affects obstacle crossing (disengagement, shifting or reengagement) or if it is a combination of the components.

Conclusions

In conclusion, this study illustrated that the orienting component of attention is correlated to obstacle avoidance of the lead foot immediately following a concussion. When attention is divided during obstacle crossing, trailing foot avoidance is also correlated to the ability to orient attention. By contrast, healthy individuals showed no correlation between obstacle avoidance and spatial orientation of attention. It is widely held that obstacle avoidance and certain components of spatial orientation of attention are specific to areas around the intraparietal sulcus, and our work supports a functional correlation between the two. We believe the contrast between healthy individuals and concussed participants to be the result of decreased attentional capacity following mild brain injuries as described in the literature [11, 19, 37, 76]. The results of this study are one of the first steps in describing the functional outcomes of decreased spatial orientation of attention following concussion. Poor performance during obstacle avoidance could lead to trips, falls and subsequent concussions that have shown to increase the likelihood of permanent brain damage during recovery from an initial concussion [57, 93, 107]. However, results from this study indicate that susceptibility to obstacle contacts due to deficits in spatial orienting attention may be temporary if present at all, and that a spatial orienting ANT task may be well suited for identifying possible susceptibility.

During the recovery process particular attention must be paid towards decreasing the likelihood of re-injury. This study indicates a coupling between spatial orientation of attention and obstacle avoidance, and that the ANT may be used to understand a person's likelihood of a trip during recovery without expensive motion analysis testing. With this information in hand, the clinician can then appropriately warn patients about these risks. Education on the implications of such trips and subsequent concussions are one method for reducing trips in such individuals. Spatial attention training might also help TBI individuals, which suffer longer lasting attentional deficits, avoid obstacle contacts. Although a single obstacle type was analyzed in this study, spatial attention deficits are used in an assortment of daily tasks that could also be detrimental if performance is diminished.

Bridge

This was one of the first studies to look at the interaction between gait performance and attention. This study uniquely looked at how one of the components of attention (spatial orientation) correlates with obstacle avoidance during gait. It clearly showed an interaction between the two, but also showed that some other components of attention did not correlate with obstacle avoidance. However, obstacle avoidance is only one component of gait performance, and not the major focus of most of this dissertation. In the final study we analyzed the interaction between dynamic balance control and two components of attention: conflict resolution and attention capacity.

CHAPTER VI

IS CONFLICT RESOLUTION OR ATTENTION CAPACITY AFFECTING DYNAMIC BALANCE CONTROL?

Introduction

Previous research has concluded an interaction between attention and balance control when the two are performed simultaneously [11, 19, 37, 70, 76, 108]. To date, it is unknown as to what component of attention is specifically interacting with motor performance to cause balance control deviations following a concussion. We suggest two possibilities: either executive functioning which presides over the conflict resolution component of attention that controls inhibition of information to maintain specific goals in mind, or a reduced attentional capacity so that there is degradation in performance assuming attentional demand exceeds attentional capacity.

Conflicting information is common in everyday situations. How we weight information and incorporate all additional information determines accuracy and timing of a correct response. The conflict resolution component of attention allows one to use information that is of particular relevance to enhance the response while blocking distracting stimuli that would lead to an incorrect response if utilized. Conflict resolution falls under the duties of the central executive to choose the correct response. Executive functioning following a concussion or more severe TBI has been extensively explored in the literature. Assessments of patients' awareness of (or lack of) their own executive dysfunction has even been reported [39]. Hart et al. found that TBI subjects scored lower on tests of executive functioning and also consistently under-reported their executive dysfunction and reduced attention. Executive dysfunction as a whole has also been shown to coincide with poor performance on tests of problem solving following concussions [40]. While most research in this area tests executive functioning as a whole, certain paradigms are designed to specifically analyze conflict resolution.

Most tests specifically of the conflict component show effects due to concussion as well. While performing a multitude of attentional tests on a TBI group of wide ranging severity, Chan and colleagues found that reduced Stroop performance occurred in all TBI subjects except those deemed to have a "normal range of attentional performance" on attentional tests [41]. In a group of predominantly mild concussed subjects, the same conflict resolution effect (measured with the Stroop task) was exacerbated [42]. Likewise, the use of the attentional network task yielded conflict resolution deficits in a group of concussed subjects up to one month post injury [20].

Motor deficits following concussion have been slightly less researched. A group of predominately mild TBI subjects were reported displaying deficits in finger tapping up to a year post-injury [72]. Severe TBI subjects have shown instability while performing obstacle crossing a year after injury [18]. Concussed young adults showed decreased gait stability during an attention dividing task a month post-injury [19]. Recently, tests of gait stability during an attention dividing task have been proposed as an alternative method for assessing resolution of deficits following concussion [11, 70]. When compared to other gait scenarios, gait with a secondary question and answer task was found to better differentiate a concussed individual's changes in gait stability from healthy controls within two days post-injury. However, secondary task performance could not be easily quantified and examined using such a Q&A task, no longitudinal comparisons to other secondary tasks exist, and such a secondary task cannot be attributed to an injury in any one cognitive component. A quantitative secondary task could provide better insight into secondary task performance and its relationship to gait stability.

The first purpose of this experiment was to analyze the effects of conflict resolution, and by doing so executive functioning, on gait stability following a concussion, and the effects of gait on conflict resolution. We hypothesized an executive function task to result in only minor gait stability changes; however, the cognitive analysis of conflict resolution was expected to be effected as a result of the gait task following a concussion. This will indicate how concussed patients resolve issues with executive functioning to maintain gait stability. This second purpose of this study was to examine how tasks in a cognition/motor dual task situation interact following concussions. An interaction was hypothesized based on well understood data in healthy individuals [109, 110], but how exactly this with present itself following a concussion is unknown. This will indicate how concussed patients resolve issues with performing multiple simultaneous tasks. Information from this study would hopefully indicate, or eliminate, certain attention deficits as the culprit for balance deficits. This in turn will inform clinicians as to what symptoms may be more important to focus on in the recovery of normal functioning.

Methods

Ten participants suffering from a grade 2 concussion (mTBI) were identified from within the University of Oregon student population (5 females/5 males; age = 21 ±3.1 years; mass = 71.68 ±10.5kg; height = 173.6 ±11.5 cm). All participants were initially recruited for testing within 2 days following the injury after identification by certified athletic trainers and/or attending medical doctors in the university intercollegiate athletic program or the student health center. Subsequent testing occurred 6, 14 and 28 days after the injury. The severity of the injury was categorized by the attending certified athletic trainers and/or medical doctors in accordance with the definitions originated by the American Academy of Neurology [73]. A grade of "2" was assigned if the participant remained disoriented for greater than 15 minutes, but did not lose consciousness for any period of time. Age-, gender-, athletic participation-, education level-, height- and mass-matched (age = 20.7 ±4.1 years; mass = 72.6 ±10.5 kg; height = 172.7 ±11.6 cm) control participants (Cont.) were recruited from within the same university population and tested at the same intervals. All of the participants signed a consent form approved by the local university human subject's compliance committee prior to partaking in this study.

All data were collected in the Motion Analysis Laboratory of the University of Oregon. Twenty-nine retroreflective markers were attached to anatomical landmarks [51]. Three dimensional marker trajectories were collected with an eight camera motion tracking system (MotionAnalysis Corp., Santa Rosa, CA) at a sampling frequency of 60 Hz. The cameras were positioned surrounding an eight-meter walkway. Ground reaction forces in three orthogonal directions and moments about the three axes were collected at a sampling rate of 960 Hz with two in-series strain gauge force plates (Advanced Mechanical Technologies Inc. Watertown, MA) flush with the top surface of the floor in the center of the walkway.

Tasks for answering the research question at hand included (1) single-task level walking, (2) a seated auditory Stroop task by which conflict resolution was examined and (3) walking with an auditory Stroop task. The auditory Stroop task required a subject to listen to a computer announced word that was presented in either a high or low tone. The word announced was either the word "high" or the word "low." The objective of the subject was to declare the tone of the word while ignoring the context of the word. Congruent presentations where the tone matches the word and incongruent presentation trials were examined separately to measure the Stroop effect. They were combined together to measure attention capacity effects.

Walking trials were performed in blocks of eight. The order of walking trials was randomized for each subject and each day. Walking was performed at a self-selected pace. During Stroop walking, a single stimulus was presented at the beginning of the analyzed motion data, as the subject was about to step on the first force plate. Subjects were informed about the impending task at the beginning of each block of trials. Blocks of four seated Stroop trials were performed before and after walking trials.

Besides recording response accuracy, we also analyzed reaction times during the Stroop task with a radio-telemetric microphone. Voice recordings were collected at 960 Hz. Visual inspections by a single examiner determined the onset of all responses. A representative trial of Stoop stimulus and reaction time is presented in Figure 6.1.

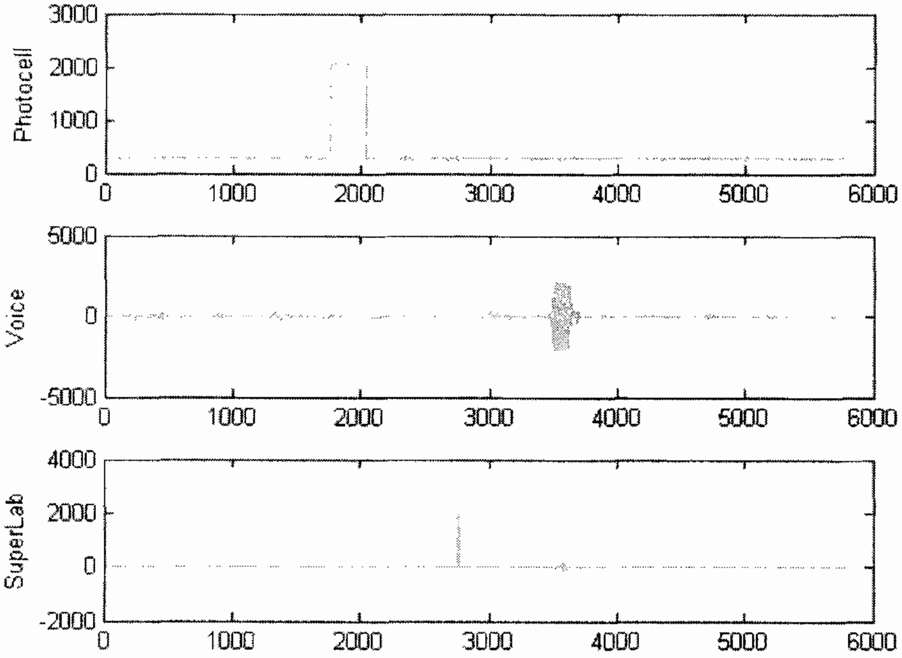

Figure 6.1. A representative output of a single trial displaying the analyzed stimulus (Superlab) and reaction time (Voice).

Marker trajectories were filtered with a low-pass fourth order Butterworth filter at a cutoff frequency of 8 Hz. Marker position data were used to locate the segmental centers of mass (CoM) of a thirteen-link model including: head, trunk, two upper arms, two lower arms, pelvis, two thighs, two shanks and two feet, based on Dempster's [77] anthropometric data. A weighted sum method was used to calculate the whole body CoM from segmental CoMs during each time point. CoM data were analyzed between the first heel strike on to the first force plate to the next heel strike of the same foot, and individual gait events will be identified for further processing. CoM velocities were estimated with the use of Woltring's generalized cross-validated spline algorithm.[78] Center of pressure (CoP) data were calculated for all time points that the subject is in contact with a force plate. Laboratory written programs (Motion Analysis Lab, University of Oregon) in Matlab 7.0 (Mathworks Inc., Natick, MA) were used to complete the processing of the data during one complete stride. CoM data were synchronized with CoP data for a complete stride.

Inclination angles were calculated as the angle from the CoM, down to the CoP and back up to the vertical (Figure 6.2). The peak inclination angles in the sagittal and coronal plane were identified. The posterior and anterior peak angles were then summed to find a sagittal plane angular range of motion (SR). The medial peak angle from the left foot was summed to that of the right foot to find a frontal plane angular range of motion (FR). Peak CoM velocities in both the sagittal and frontal plane (SV, FV) were identified.

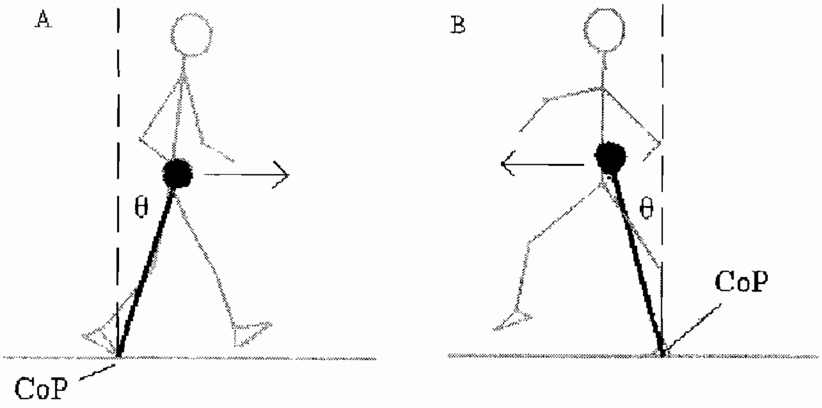

Figure 6.2. Center of mass to center of pressure inclination angles in the (A) sagittal and (B) frontal planes.

A three-way mixed model analysis of variance with repeated measures (alpha = .05) was conducted on each variable using SPSS v.12 (SPSS Inc., Chicago, IL). The appropriate assumptions for both within and between subjects ANOVA were considered. Simple effects were then analyzed with adjustments for multiple comparisons (.05/8 = alpha = .00625).

To analyze how each group as whole altered one task performance with respect to the other in the dual task situation we calculated correlations between the means of balance variables and Stroop reactions times with linear regressions for each group and day (alpha = .05). To analyze how each individual altered one task performance with respect to others in the dual-task situation we calculated correlation coefficients for each individual and then conducted a two-sample t-test between groups (alpha = .05).

Results

Group Mean Comparisons

Within these results we will discuss the comparisons we have made generalizing concussed individuals into one group using analyses of variance. Analyses on Stroop reaction time separated by group, testing day and task specifics (congruency and motor paradigm) indicated no statistically significant differences. Likewise, there were no statistically significant differences in peak medial velocity of the CoM. All other variables proved statistically significant.

Both peak anterior CoM velocity and angular range of motion in the sagittal plane indicate group*day interactions (p = .015 and p = .004, respectively) and task differences (p = .021 and p = .003, respectively). Group*day interactions indicate that only concussed individuals walk with significantly slower sagittal COM motion (Figure 6.3) and allow less sagittal plane CoM-CoP angular separation (Figure 6.4) on the first testing day compared to all other testing days. Both groups walk with significantly slower peak velocities and allow significantly less sagittal plane CoM-CoP separation during single task walking compared to Stroop walking.

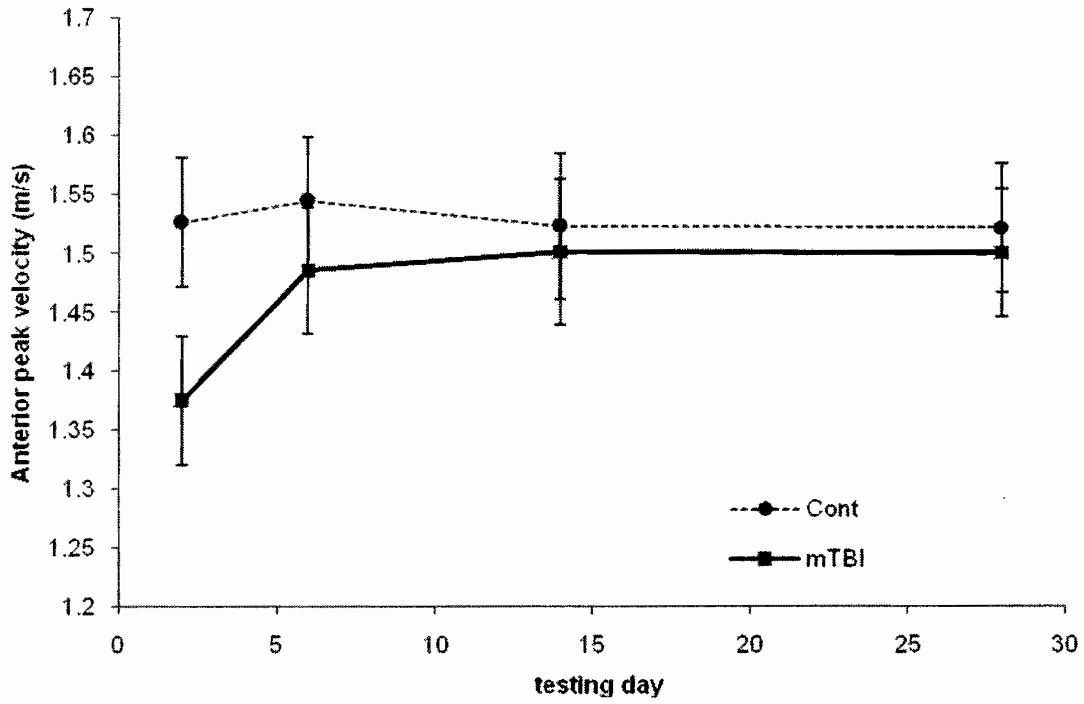

Figure 6.3. Anterior peak velocity of center of mass over 28 days of testing for each group. Controls are represented by the dashed line. Concussed are represented by the solid line. Standard error bars are presented.

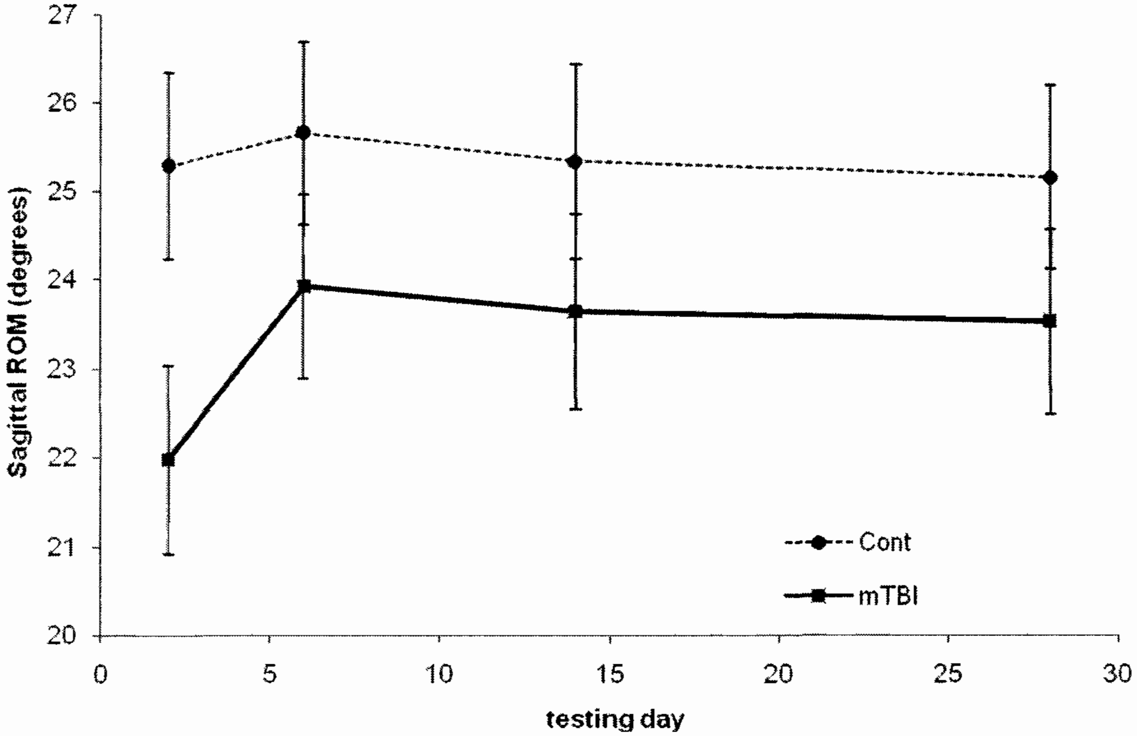

Figure 6.4. Sagittal plane angular range of motion of the center of mass with respect to the center of pressure over 28 days of testing. Controls are represented by the dashed line. Concussed are represented by the solid line. Standard error bars are presented.

Analysis of variance on frontal plane angular range of motion of the CoM (Figure 6.5) indicates a group*day*task interaction ($p = .003$). The concussed group in general tended to have more frontal plane motion than controls during gait, but specifically showed increased motion during congruent Stroop walking on the 14 day testing ($p = .006$). This difference was not due to the fact that control individuals changed, as they did not have any statistical difference between days, but concussed individuals did have increased frontal plane motion during congruent Stroop walking on day 14 compared to day 7 ($p = .002$) and day 28 ($p < .001$) post-injury. Concussed frontal plane motion during congruent Stroop walking on the 14 day testing was also significantly greater than single-task walking on the same day (p = .003).

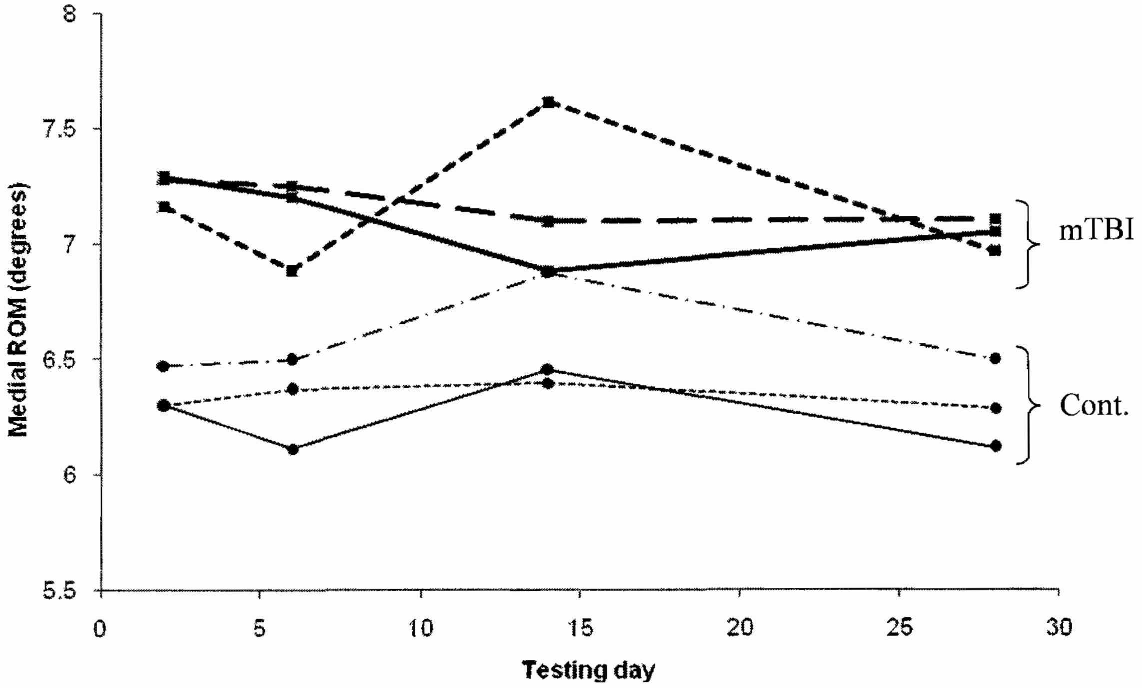

Figure 6.5. Medial angular range of motion of center of mass with respect to center of pressure over 28 days of testing. Concussed subjects are represented by "mTBI" to the right of the graph and control subjects are represented by "Cont." Solid lines represent single task walking, highly perforated lines represent Stroop walking during congruent task presentation and slightly perforated lines represent Stroop walking during incongruent task presentation.

Correlation Analyses

In this section of the results we explain how secondary task performance interacts with walking performance in each group and within subjects. First, control individuals demonstrated no correlation between sagittal plane motion and Stroop performance. On the other hand, concussed individuals showed significant moderate correlations between sagittal plane motion and Stroop performance during gait 48 hours after injury (R^2 = .411, p = .046), which reduced to non-significant levels on each subsequent day, but not to shared variance levels of control individuals. The relationship showed that concussed individuals who displayed greater sagittal plane CoM-CoP angles required longer reaction times (Figure 6.6).

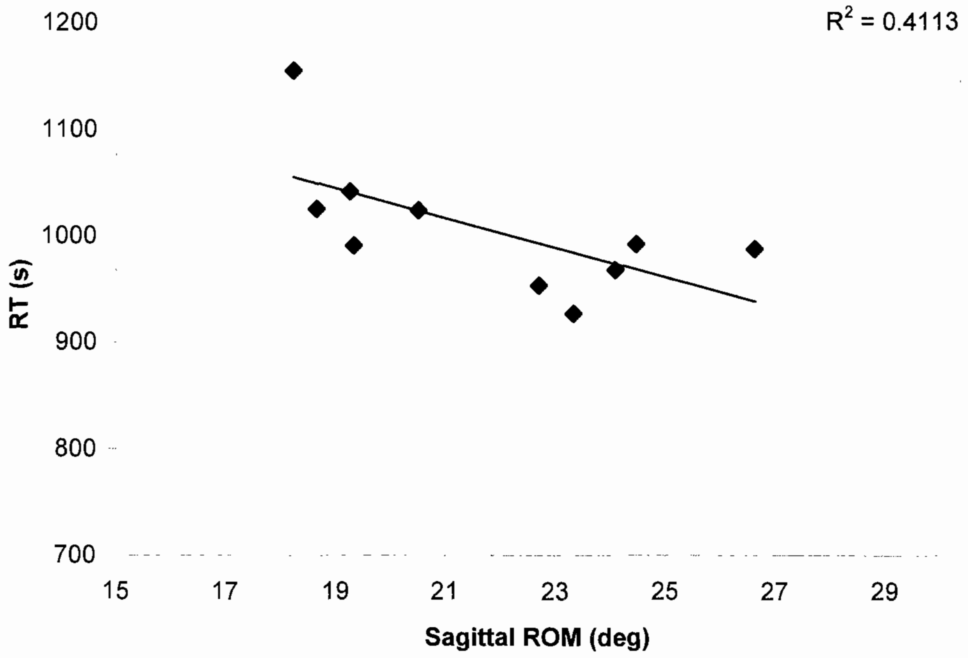

Figure 6.6. Correlation between sagittal plane angular range of motion of the CoM with respect to the CoP and Stroop reaction time for concussed individuals on the first testing day. Each point represents the mean performance of a single individual 48 hours after injury.

When specifically looking within each individual we found that seven of the ten concussed individuals displayed a positive correlation between Stroop reaction time and sagittal angular range of motion 48 hours after injury (Figure 6.7), indicating an increase in one may correlate with an increase in the other. This was statistically different than control individuals that displayed no correlation or just the opposite correlation within most individuals (p = .048). There were no differences between the correlation coefficients of each group on subsequent testing days.

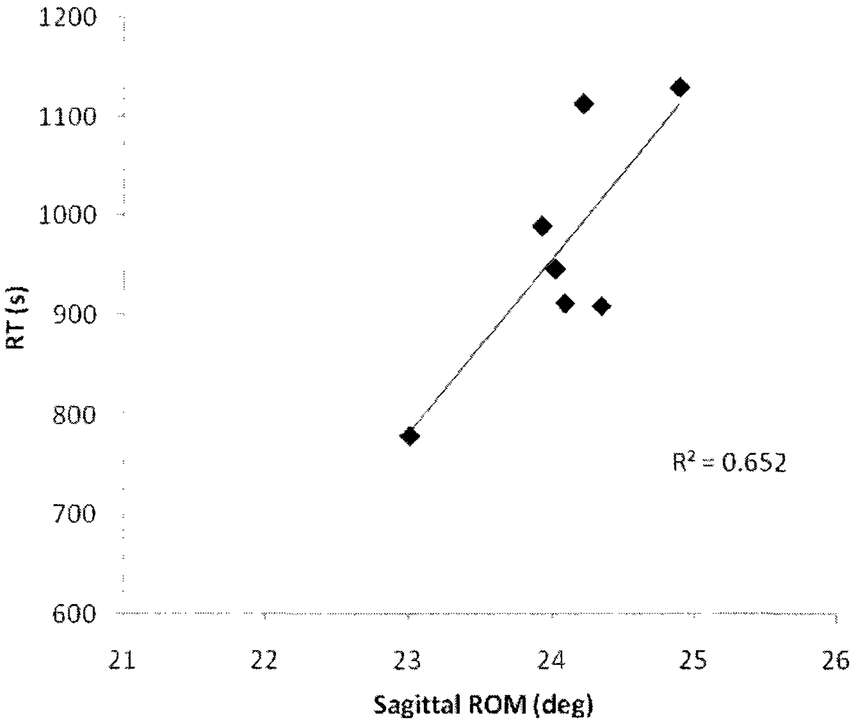

Figure 6.7. A typical pattern of trial performances indicating the correlation that most concussed individuals displayed between sagittal angular motion during gait and reaction time in the Stroop task 48 hours after injury. Each point represents a single trial's performance 48 hours after injury for this particular concussed individual.

Discussion

The two purposes of this research were to (1) examine the relationship between executive functioning (through a conflict resolution task) and dynamic balance control and to (2) examine the relationship between task performances in a dual-task situation; both following concussion and in healthy individuals.

Conflict Resolution – Balance Control

An interaction between conflict resolution and dynamic balance control would be evident with a difference in either Stroop performance or dynamic balance control between congruent and incongruent conditions. The single possible indication of a conflict resolution interaction with dynamic balance control following concussion occurred in the 14 day testing. Concussed individuals performing a congruent Stroop task had more coronal plane motion than when they were performing single task walking. Incongruent Stroop walking did not result in the same increased coronal plane motion. However, since there was no statistical difference between congruency conditions then this is only a speculative difference until an increased sample size can shed more light on this particular trend. If this was supported with an increased sample size then one possible explanation might be a somewhat similar finding that Parker and colleagues [19] noticed from concussed individuals when they had a steady decrease in coronal plane motion during walking with a divided attention task until several weeks after their injury when their coronal plane motion increased again. They attributed this increase to a return to normal activity that might have led to sub-concussive incidents. So why then is this not seen in the incongruent Stroop task in our study? It might be that this task is particularly challenging to the point that more attention is devoted to properly controlling balance as was seen in the second study of this dissertation when dual-task obstacle crossing led to decreased coronal plane motion. Not seeing group differences just after injury also does not refute our findings since it might be that the return to normal activity resulted in further deteriorations after the initial concussion as was suggested previously [19].

Task Interactions

Task interactions were much more evident in this study. Since there were few congruency differences all the dual-task trials were averaged to calculate the means of balance parameters and Stroop reaction times for the analysis of interaction between the two in each group. With this analysis we found that concussed individuals that had slower reaction times also used a more cautious gait strategy with decreased angular CoM motion about the CoP. A similar conservative gait strategy has been found in mild [11, 19, 70, 76] and more severe [18, 35] brain-injured individuals. This interaction indicates that within the group of concussed individuals there are individuals that may be more impaired than others in the group. Those that do suffer more impairment have an average cognitive processing deficit along with an average slowing of motor performance in a dual-task situation compared to those that may have more mild symptoms or may at the time be completely recovered. This is supported by findings that severely brain injured individuals performed poorly in postural control while at the same time committing more arithmetic errors in a dual-task paradigm [108]. This information shows the importance of diagnosing a concussion beyond simple grading scales that categorizing concussion subjects of varying severity into the same patient group. This interaction was only dominant in the first testing session, after which it gradually decreased. Presumably, this is due to symptoms, that concussed individuals suffered soon after injury, eventually subsiding.

In the analysis of individual concussed participants we looked at trends in balance/cognition interactions between trials for each individual. We then used that information to distinguish between concussed and control individuals. Within each concussed individual (between trials) on the first testing day we found that most individuals had a trade-off in performance of tasks in the dual-task situation. For certain trials they either had quicker reaction times and with more cautious sagittal plane motion and for other trials they had slower reaction times with less cautious gait performance. This interaction was not present in control individuals in the first testing session. In subsequent testing sessions there were no statistical differences between how concussed and control individuals varied secondary task performance with walking strategy. This interaction and resultant trade-off has not been previously examined in concussed individuals during a dynamic motor task, but it is similar to what control individuals have displayed in coordination/reaction time tasks [109, 110]. The fact that we are not seeing this trade-off in control individuals for the particular paradigm used in this study is promising in the fact that it might indicate no challenge to control individuals, but may be challenging to concussed individuals, making the task particularly sensitive to the effects of concussions. Trade-offs in task performances seem to be a result of limited attentional resources indicated in the group correlations, similar to previous findings [109]. These interactions only immediately after concussion are particularly noteworthy since our previous research has shown dual-task balance deficits immediately after concussion [11, 19, 70, 76], but slowly subsiding there after [19].

Conclusions

In conclusion, even though attention deficits have been previously shown to be related to balance control after concussion, there were no indications that dynamic balance control was affected by executive function deficits, but it should be noted that deficits were not even noted in the seated trials, possibly indicating a low trial sample size given the variability between trials. On the other hand, changes in gait due to concussion were evident in individuals that also had slower reaction times in the secondary Stroop task. While analyses of the concussed group as a whole indicates that those that have deficits in one task also suffer deficits in the other, the analyses of inter-trial task performances within the concussed group showed most individuals used a trade-off in task performances while controls did not show this trend. This only occurred on the first testing day. This information points to attentional capacity deficits as the possible culprit in gait abnormalities following a concussion.

CHAPTER VII

SUMMARY OF FINDINGS AND CONCLUSIONS

Major Findings

The research presented here focuses on two major aspects of dynamic balance control following a concussion. The objective of the first two studies was to explore the different gait tasks that have been previously suggested as perturbing to concussed individuals. In turn, this would provide information on how the same concussed individuals might handle different gait tasks and also which, if any, of the tasks might be sensitive to the presence of concussion motor deficits prior to a premature return to normal activities. From these two studies, which tested single task level-walking and obstacle-crossing and divided attention level-walking and obstacle-crossing, we determined that neither the most simple task (single task level walking) or the most difficult task (divided attention obstacle crossing) were appropriate for distinguishing concussed individuals from healthy controls. The obstacle crossing task was able to distinguish concussed individuals by 14 days after the injury, when concussed seemed to show a more conservative balance strategy due either to regained control of balance or appropriate allocation of resources devoted to balance. The divided attention level walking task distinguished concussed individuals early after their concussion indicating the importance of attention in balance control particularly after a concussion. This became even more clear the last two studies.

The last two studies explored the interaction between different components of attention and gait performance. Given the first two studies, I believe attention interacts with gait performance in a crucial way, but from these studies I was unable to determine how. The third study in this dissertation was meant to provide information as to how the spatial orientation component of attention interacts with obstacle avoidance following a concussion. I found that spatial orientation, rather than conflict resolution or alertness, interacted with obstacle avoidance during gait. Concussed individuals that had spatial orientation deficits also had a less safe obstacle avoidance strategy. This interaction intensified when attention was divided during obstacle crossing, indicating attention capacity deficits as well in concussed individuals. Controls displayed no such interactions. This shows that an examination of spatial orientation deficits can explain how well a concussed patient can avoid physical obstacles in an environment.

The final study explored the interaction between tasks in a dual task paradigm and the interaction between executive function and dynamic balance control. I found that executive functioning may not interact with dynamic balance control. However, there were clear task interactions. Concussed individuals that had poor performance in a cognitive task also performed poorly in the motor task. A trade-off between performances of each task was employed by concussed individuals. The findings indicate that attentional capacity may be to blame for dual-task balance deficits that studies performed by separate researchers and the first study in this dissertation found are present in concussed individuals.

Limitations of the Study

Of course, this research is not without its limitations. Our goal as researchers is to discover what and why things occur the way they do. But, inherent to research is that it does not completely and perfectly replicates real world conditions. So we are left to make some assumptions that might be appropriate, but also might introduce errors to our analyses.

Sample size can be a particular concern in any human testing. We want enough subjects to be a good representation of the overall population. With the inclusion criteria of grade 2 concussion within our student body population it was difficult to gather a large portion of subjects that were willing to complete multiple testing sessions in various laboratories. Our first two studies had more than 30 subjects involved, which we thought a decent sample size. Studies 3 and 4, however, had 17 and 10 subjects respectively in each group. I believe each of these were enough to clearly represent the population since both sample sizes produced statistical significance in their respective studies. My only question to this was in the fourth study when I predicted there to be at least some differences in conflict resolution performance between concussed individuals and controls, since others have previously shown this difference. Perhaps with a sample size of more than 10 individuals in each group we might have uncovered such difference. Prudence should be directed towards an increased sample size in similar future studies

One thing a larger sample size corrects for in analyses using group means is natural human variability between different people. The first two studies of this research relied on group averages to supply an understanding of how a concussion affects gait. Larger sample sizes in these studies eases concern about human variability. The third study also used a regression analysis that treats each person as a data point in the study, avoiding the limitation of variability between individuals. However, this does not avoid the variability between different trials. We did try to account for trial variability by collecting multiple trials, but were not reasonably able to collect so many trials to remove any question of an accurate average performance. In the last study, we focused an analysis down to the examination of trial variability, avoiding this limitation.

Another change that occurs over the course of a testing day between trials is the effect of becoming more comfortable with the required tasks. In the cognitive task this comfort takes the form of a learning effect. We removed this effect by randomizing the order or congruency tasks in the forth study. However, since we were examining interactions between cognitive and motor tasks in our study through different trial block types, we also should be concerned with individuals gradually becoming more comfortable with walking in our lab under examination and with a full marker set during a particular testing session. In the first three studies the trial block order was always the same (LEVEL, OB, Q&A and D-OB). This could pose some problems in the differences between tasks. However, since our comparisons were mainly concerned with group differences, the block order was not so much of a concern except for interactions found in an ANOVA analysis. This was corrected for in the final study with a randomization of trial blocks. Also a concern with the comfort effect is that all individuals were tested over time, but once again this would only concern us if it affected interactions involving group differences.

The final major limitation of this research is quantification of the secondary task in studies one through three. Quantification of the secondary task is important because an individual may perform normally in the primary motor task in the dual-task paradigm but might have altered secondary task performance. If this is the case, then an interaction effect between the two tasks is just as evident as if the individual altered primary task performance. We attempted to quantify the secondary task in the first three studies, but the variables of the secondary cognitive task were not completely continuous, but rather they only allowed for whole number values to be measured. There were only so many responses we could record given the limited time of each trial, so any one point change from one trial to the next would account for a much larger percent change, increasing the overall variability and decreasing the precision of our secondary measures. With the inclusion of the verbal reaction time to the Stroop task in study four we were able to collect much more precise values (down to the milliseconds). This more continuous function allows for decreased variability between trials due purely to precision.

Suggestions for Future Studies

The studies included in this dissertation have shed some light on the interaction between attention and dynamic balance control following a concussion. However, the last major finding of this research is that further investigation into the questions posed in this research is still required.

Over the past two decades there has been a shift towards a more quantitative analysis of balance control using several different models. We model the human body as an inverted pendulum where the system becomes imbalanced if the center of mass travels to far from the center of pressure. However, this is just one approach to quantifying balance control. Measurements of joint coordination, muscle recruitment or stride variability have been used successfully in the past to model balance. It might be that any one of these methods could prove more appropriate and a better distinguisher of balance control following concussion.

We have shown in this study that our balance control variables measured during different tasks were able to distinguish concussed individuals at different times in their recovery. However, these data are not complete. We have no way of knowing how the concussed individuals performed prior to their concussion. The ease of collecting matched control subjects rather than baseline testing a large possible cohort is at the sacrifice of not knowing true normal values for our concussed individuals. Baseline information would be useful in knowing if there were previous motor deficits that were the cause of the concussion rather than a symptom of the concussion. Baseline information will also provide a better method of comparison rather than a control group that introduces natural human variability into the equation. We also have shown that at about two weeks post-injury obstacle crossing performance changes in concussed individuals. However, we cannot determine how or even if obstacle performance returns to normal by only testing out to a month post-injury.

While the tasks used in this study to measure balance control seem to be sensitive to the functional effects of concussion, further research might explore comparisons between other tasks of daily living. Prior to this an epidemiological study of how secondary concussions occur would be essential. One of the major assumptions of this dissertation is that secondary concussions may occur because of balance control deficits caused by the first concussion. However, it might be that individuals are more likely to incur a second and third concussion only because they are involved in activities that predispose them to concussion causing events.

While exploring all the different avenues of balance control following a concussion is needed, a mark of any good scientific study and a requirement before any of it moves from findings to theory is that it be replicated to produce similar results. There are few groups in the scientific community that have taken up the endeavor of trying to quantify the interaction between balance control and attention following a concussion. To some it is because a concussion is deemed insignificant to the point that any research would be pointless. Clearly there has been a positive trend away from this viewpoint as more and more individuals are showing some long-term deficits due to once thought to be only minor concussions. Others view an individual concussion as too transient or variable to get a quick and complete grasp. I, in fact, fully agree with this assessment, given our current knowledge. But it does not have to be this way if more than just a few groups take the initiative to advance our scientific understanding of "concussion."

Finally, a shift towards the clinical implementation of these findings is also needed after factors affecting balance control have been fully explored. The refinement of clinical assessments that accurately and precisely measure balance control deficits following a concussion is the ultimate goal so that a clinician can perform a complete, yet practical, examination of symptoms to judge the appropriateness of a return to normal activities.

APPENDIX A

INFORMED CONSENT FORM (MTBI)

CONSENT FORM

You are invited to participate in a research study conducted by Drs. Li-Shan Chou, Louis Osternig, and Paul van Donkelaar of the University of Oregon, Department of Human Physiology. We hope to gain a better understanding of the biomechanical and sensorimotor mechanisms underlying the decreased stability in individuals suffering from mild traumatic brain injury (i.e., concussion).

If you decide to participate, you will be tested over several separate sessions in the Motion Analysis and Eye-Hand Laboratories and in the Center for NeuroImaging at the University of Oregon.

Tests in the Motion Analysis Laboratory

The tests in the Motion Analysis Lab 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 and the muscle activity of five muscles from both legs. Your body movement (indicating by motion of reflective makers) during walking and obstacle crossing will be recorded by our optoelectronic cameras (or may be video cameras upon your approval) for further analysis. You 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 the above-mentioned tests.

Tests in the Eye-Hand Laboratory

The tests in the Eye-Hand Lab will consist of viewing visual stimuli presented on a computerized display and reacting to these stimuli with eye and/or hand movements. To record eye movements we will use a device that projects infrared light into the eye. We will also make a dental impression bar for you to bite on during the eye movement testing. This is required to stabilize the head. Hand movements will be measured with button presses. It will take approximately 1.5 to 2 hours to perform these tests.

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 possibility of discomfort involved in removing adhesive tape (used for marker placement) from skin at the end of the experiment, and wearing the eye movement monitor. Although you personally will not receive any benefits from this research, based on results of this study more effective therapies, rehabilitation programs, or balance assistive devices for the prevention of falls in a number of patient populations may be designed and implemented.

Tests in the Center for NeuroImaging

For tests in the Center for NeuroImaging you will be asked to briefly practice and then perform a task requiring eye and/or hand movements to a visual target while we take pictures both of your brain's structure (standard MRI) as well as blood flow in your brain (functional MRI). During these procedures you will lie on a table inside a high field magnet. There is no ionizing radiation (like X-rays) used in these studies. This study will not require any invasive procedure. You will be asked to lie still and we will cushion your head with some soft foam. Strapping across your chest will minimize the extent of head motion. You will be asked to look at and point to a target presented through a projection and mirror system. When the target changes position, you will be required to make an eye and/or hand movement to the new target location. All testing is carried out with the magnet will be conducted by a trained technician.

RISKS AND DISCOMFORTS: The tasks may cause some fatigue. You may ask to discontinue testing at any time. Each visit(s) will last from 1 to 1.5 hours. There are no known risks of functional MRI. However, some individuals with claustrophobia (fear of closed spaces) may find the MRI equipment too confining. In that case, you can request to be removed from the scanner and this will be done immediately. The MRI scanner makes a loud "beeping" sound. You will be required to wear protective earplugs during scanning.

Should we be concerned about the results of the MRI scan we will refer the scan to a radiologist and you will be informed. If you so desire, your physician can be contacted regarding our findings. There are no known risks of this procedure to a fetus. However, if you are sexually active and capable of becoming pregnant, you must use an effective method of birth control while participating in this research. If you become pregnant during the study, you will no longer be used as a subject for this MRI research study.

You cannot have an MRI if you have any metal in or near your brain such as an aneurysm clip, a pacemaker for your heart, a cochlear implant, or metal body parts (like a heart valve, hearing aids, etc.) For example, welders and metal workers may be in danger because they may have small metal fragments in their eyes. This would be dangerous inside the magnet. There are also possible risks for participants if metal objects are drawn to the magnet while a participant is within or near the bore. Accordingly, you will be asked to leave all jewelry and metal objects outside of the testing area. No loose metal objects will be allowed near the magnet. There may be some unanticipated risks or side effects involved with your participation in this research study. To date, there is no evidence that high magnetic fields endanger health on a short or long term basis.

Any information that is obtained in connection with this study and that can be identified with you will remain confidential and will be disclosed only with 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.

Your participation is voluntary. Your decision whether or not to participate will not affect your relationship with Peace Health, the Department of Human Physiology or University of Oregon. You do not waive any liability rights for personal injury by signing this form. All forms of medical diagnosis and treatment, whether routine or experimental, involve some risk of injury. In spite of all precautions, you might develop medical complications from participating in this study. If such complications arise, the researchers will assist you in obtaining appropriate medical treatment, but Peace Health does not provide financial assistance for medical or other costs. In addition, if you are physically injured because of the project, you and your insurance company will have to pay your doctor bills. If you are a University of Oregon student or employee and are covered by a University of Oregon medical plan, that plan might have terms that apply to your injury.

If you decide to participate, you are free to withdraw your consent and discontinue participation at any time without penalty. A total of 4 testing sessions over a period of 28 days are required for you to complete your participation in this study. You will receive $100 for completing each testing session.

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. If you have questions regarding your rights as a research subject, contact Human Subjects Compliance, University of Oregon, Eugene, OR 97403, (541) 346-2510 or Peace Health IRB, 1255 Hilyard St. Eugene, OR 97401, (541) 696-6949. 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.

Name: ____

Signature: ____

Date: ________________________________

APPENDIX B.

INFORMED CONSENT FORM (CONTROL)

CONSENT FORM
(Control Subject)

You are invited to participate in a research study conducted by Drs. Li-Shan Chou, Louis Osternig, and Paul van Donkelaar of the University of Oregon, Department of Human Physiology. We hope to gain a better understanding of the biomechanical and sensorimotor mechanisms underlying the decreased stability in individuals suffering from mild traumatic brain injury (i.e., concussion).

If you decide to participate, you will be tested over several separate sessions in the Motion Analysis and Eye-Hand Laboratories. The tests in the Motion Analysis Lab 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 and the muscle activity of five muscles from both legs. Your body movement (indicating by motion of reflective makers) during walking and obstacle crossing will be recorded by our optoelectronic cameras (or may be video cameras upon your approval) for further analysis. You 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 the above-mentioned tests.

The tests in the Eye-Hand Lab will consist of viewing visual stimuli presented on a computerized display and reacting to these stimuli with eye and/or hand movements. To record eye movements we will use a device that projects infrared light into the eye. We will also make a dental impression bar for you to bite on during the eye movement testing. This is required to stabilize the head. Hand movements will be measured with button presses. It will take approximately 1.5 to 2 hours to perform these tests.

We expect that there will be no more risk for you during testing 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 possibility of discomfort involved in removing adhesive tape (used for marker placement) from skin at the end of the experiment, and wearing the eye movement monitor. Although you personally will not receive any benefits from this research, based on results of this study more effective therapies, rehabilitation programs, or balance assistive devices for the prevention of falls in a number of patient populations may be designed and implemented.

Any information that is obtained in connection with this study and that can be identified with you will remain confidential and will be disclosed only with 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.

Your participation is voluntary. Your decision whether or not to participate will not affect your relationship with the Department of Human Physiology or University of Oregon. If you are physically injured because of the project, you and your insurance company will have to pay your doctor bills. Your University of Oregon medical plan might have terms that apply to your injury.

If you decide to participate, you are free to withdraw your consent and discontinue participation at any time without penalty. A total of 4 testing sessions over a period of 28 days are required for you to complete your participation in this study. You will receive $100 for completing each testing session.

If you have any questions, please feel free to contact Dr. Li-Shan Chou, (541) 346-3391, Department of Exercise and Movement Science, 112C Esslinger Hall, University of Oregon, Eugene OR, 97403-1240. If you have questions regarding your rights as a research subject, contact Human Subjects Compliance, University of Oregon, Eugene, OR 97403, (541) 346-2510. 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.

Name: ______________________________

Signature: __________________________________

Date: ________________________

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