THE EFFECT OF CONCUSSION HISTORY ON STATIC AND DYNAMIC BALANCE IN COLLEGIATE ATHLETES

by

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(Under the Direction of DR. JULIANNE SCHMIDT)

ABSTRACT

Dynamic balance deficits exist following a concussion, sometimes years after injury. However, clinicians lack practical tools for assessing dynamic balance. The purpose of this study was to determine if there was a significant difference in static and dynamic balance performance between individuals with and without a history of concussion. Participants were placed into a concussion history group or a matched control group with no previous history of concussion and completed the Y Balance Test-Lower Quarter (YBT-LQ) and Balance Error Scoring System (BESS). No significant differences were observed between groups in YBT-LQ reach distances or BESS errors. This study indicates that no deficit in long-term clinical static or dynamic balance test performance exists in collegiate athletes with a general history of concussion.

INDEX WORDS: Concussion, Static balance, Dynamic balance, Y Balance Test-Lower Quarter, Balance Error Scoring System, mild traumatic brain injury

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DEDICATION

I would like to dedicate this thesis to family. To my parents and my brother, thank you for always supporting me and for teaching me to strive to make an impact. I wouldn't be in this position if it were not for you. To Jaime, thank you for your patience and understanding during this whole process. I know it hasn't been easy on you, but you never complained and always supported me. I can't thank you enough for that. Finally, to Hudson, I hope this makes you proud in the future. No matter what you do in life, do it to the best of your ability.

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CHAPTER 1

INTRODUCTION

Background

Epidemiological studies suggest that approximately 1.6 to 3.8 million sport-related concussions occur every year, many of which go unreported (McCrea 2004, Langlois 2006). In recent years, the medical community has seen a drastic increase in research interest pertaining to concussions, specifically, sport-related concussions. As defined by the Consensus Statement on Concussion in Sport, a concussion is “a brain injury and is defined as a complex pathophysiological process affecting the brain, induced by biomechanical forces” (McCrory 2013). Similarly, the American Association of Neurological Surgeons states that the most formal definition of a concussion is "a clinical syndrome characterized by immediate and transient alteration in brain function, including alteration of mental status and level of consciousness, resulting from mechanical force or trauma" (AANS 2011). Sport-related concussion was previously thought to be a functional and metabolic injury (McCrory 2013), but has since been suggested to be a structural injury (Zhou 2013).

The common symptomology of concussion includes headache, nausea, memory deficits, attention lapses, fatigue, unusual mood swings (e.g., irritability, anxiety, and depressed mood), and motor control or balance changes (Kelly 1997, Lovell 2003, Broglio 2014). Concussion symptoms typically last for a matter of days, but the recovery period can range from days to months, or even years (Guskiewicz 2003, McCrea 2003). Areas of the brain mostly related to attention, behavior, and memory experience atrophy following mild Traumatic Brain Injury

(Zhou 2013). Cingulate white matter atrophy is correlated with poorer neurocognitive function and more severe symptom presentation (Zhou 2013).

In order to best manage concussions, sports medicine professionals ordinarily require athletes to complete a baseline concussion assessment. Baseline concussion assessment provides clinicians with a pre-participation score to compare back to if an athlete later sustains a concussion. The baseline concussion assessment often consists of four aspects: clinical exam, symptom report, neurocognitive assessment, and balance assessment (McCrory 2013, Broglio 2014). Diversity in clinical presentation among concussed individuals requires clinicians to utilize a multifaceted assessment approach.

To assess balance, clinicians often test static balance using the Sensory Organization Test through NeuroCom® Balance Master (NeuroCom Co., Inc., Clackamas, OR) or Balance Error Scoring System (BESS), a static balance test performed on firm and foam conditions. Sensory Organization Test and BESS scores typically return to baseline levels by within three to five days following concussion (Guskiewicz 2001). Both assessments evaluate static balance by asking participants to remain still and maintain a quiet posture. The BESS was a component of this study due to its involvement in the concussion protocol, as well as providing a means of comparing static and dynamic balance scores.

Static balance is accomplished by the body making a series of automatic postural adjustments to maintain quiet balance (Nardone 2010) and does not involve any purposeful or intentional movements (Lephart 2000). However, postural-kinetic capacity, ("the ability to manage the perturbation to balance") (Nardone 2010), and sensory-motor integration (how well the body processes sensory information), are both essential in effectively assessing multiple balance capabilities, and may best be assessed using dynamic balance tasks (Nardone 2010).

Long-term deficits in static and dynamic balance have been found using sophisticated measures. When examined using a virtual reality task, concussed individuals present with balance deficits 30 days post-concussion with deficits persisting longer with each subsequent concussion (Slobounov 2007, Slobounov 2008). Research suggests that previously concussed individuals exhibit gait abnormalities years after a concussion. Individuals with a concussion history spend more time in the double-leg stance phase and walk at a slower speed (Martini 2011). During dual-task walking, increased center-of-mass sway in the frontal plane and increased medio-lateral separation between center of mass and center of pressure existed in concussed individuals compared to a non-concussed group, even after the athlete had been medically cleared to return to sport (Chou 2004, Parker 2005, Parker 2006). The increased sway during dual-task gait trials is still present 28 days post-concussion (Parker 2006). Concussed individuals present with impaired gait well after neurocognitive scores are back to normal (Parker 2007), suggesting a need for further research to understand the effects of concussion on dynamic balance. However, detecting gait changes may require equipment or methods that may be impractical for many clinicians. In particular, these sophisticated measures, such as approximate entropy, center of mass, and center of pressure analysis are not currently clinically feasible.

The Star Excursion Balance Test assesses dynamic balance and is administered by performing a maximum reach, during unilateral stance, in eight individual reach directions (Olmsted 2002, Plisky 2009). The Star Excursion Balance Test is well known as a quick method of assessing dynamic balance (Plisky 2006), possibly indicating its efficacy as a feasible clinical assessment tool. The Star Excursion Balance Test has been widely used to detect dynamic balance deficits in individuals with lower extremity injuries. For example, individuals with

Chronic Ankle Instability demonstrate significantly shorter reach distances when standing on their involved ankle during the Star Excursion Balance Test, compared to their uninvolved ankle (Gribble 2004), and individuals with an ACL deficiency show decreased reach distances, and thus altered dynamic balance, compared to controls (Herrington 2009). The Star Excursion Balance Test is effective, cost-efficient, and allows for possible detection of balance deficits in clinical populations (Plisky 2006). Researchers have found dynamic balance exams to exhibit excellent test-retest reliability, especially when compared to static balance assessments (Schneiders 2012). Due to its applicability for assessment of numerous pathological populations, the Star Excursion Balance Test may be suited for assessment of concussions, as well. The 8-direction Star Excursion Balance Test has been simplified to a protocol with three directions due to the sensitivity of those directions in detecting reach deficits (Plisky 2009). This test, called the Y Balance Test-Lower Quarter (YBT-LQ) when performed on a commercial apparatus, has increased reliability compared to that of the Star Excursion Balance Test (Plisky 2009). The Star Excursion Balance Test has moderate to good intrarater reliability (ICC: 0.67-0.67) (Kinzey 1998, Olmsted 2002, Hertel 2000) and poor to good interrater reliability (ICC: 0.35-0.93) (Hertel 2000). The YBT-LQ, however, has good intrarater reliability (ICC: 0.85-0.89) (Plisky 2009) and excellent interrater reliability (ICC: 0.97-1.0) (Plisky 2009).

Statement of the Problem

There is a gap in knowledge regarding the possible long-term dynamic balance deficits following concussive episodes. Research shows that concussed individuals present with abnormal gait patterns (Chou 2004, Parker 2005, Parker 2006, Catena 2007, Martini 2011, Fait 2013), well after neurocognitive and static balance deficits resolve (McCrea 2002, McCrea 2003). These studies suggest that concussed athletes may have impairments, not evident using traditional static balance measures, which persist well after the individuals are considered recovered and return to the dynamic motions required in sport. It is important for clinicians to utilize evaluation tools that are sensitive to balance impairments throughout the entire recovery process, but also feasible for clinical use, as some measures are not cost or time-effective. Therefore, the BESS was a component of this study, providing a means of comparing clinically available static and dynamic balance tools. An athlete that prematurely returns to play may be more prone to sustaining subsequent concussions and possibly more serious brain injuries (McCrea 2003, Cantu 2010, Harmon 2013). However, there is limited research regarding the long-term effects of concussions on athletes, particularly on a dynamic balance task. Although recent literature has examined gait as discussed above, many sports are not walking related. Therefore, a need exists to assess dynamic movements that are more inherent to the particular sport. In observing common concussion assessment protocols, static balance exams are often mentioned, but with a lack of attention to dynamic balance assessments. Clinicians lack a widely practical means of assessing dynamic balance. We sought to bridge the gap between previous research utilizing biomechanically intensive gait analyses and current clinical practice by examining dynamic balance using a clinically available and widely used assessment tool.

Statement of Purpose

The primary purpose of this study was to determine if there was a significant difference in static and dynamic balance performance between individuals with and without a history of concussion. The secondary purpose of this study was to determine if there was a significant relationship between static and dynamic balance performance and time since last concussion.

Research Questions and Hypotheses

1. Are there significant differences in non-dominant YBT-LQ directional (anterior-ANT, posteromedial-PM, posterolateral-PL) and composite reach distances between participants with and without a history of concussion?
    a. Hypothesis 1: The concussion history group will have significantly shorter ANT, PM, PL, and composite reach distances on the YBT-LQ compared to the control group.
    b. Independent Variable:
        i. Concussion History
            1. No history
            2. History (1 or more concussions)
    c. Dependent Variables:
        i. Anterior reach distance (% of limb length)
        ii. Posteromedial reach distance (% of limb length)
        iii. Posterolateral reach distance (% of limb length)
        iv. Composite Reach Distance (% of limb length)
2. Are there significant differences in firm, foam, and overall BESS errors between participants with and without a history of concussion?
    a. Hypothesis 2: There will not be a significant difference in the number of errors among the firm, foam, and overall BESS conditions between groups.
    b. Independent Variable:
        i. Concussion History
            1. No history

        2. History (1 or more concussions)

    c. Dependent Variables

        1. Firm condition errors
        2. Foam condition errors
        3. Overall errors

3. Are there significant correlations between YBT-LQ directional and composite reach distances the time since last concussion among the concussion history group?
    a. Hypothesis 3: There will be a significant positive relationship between time since last concussion and YBT-LQ anterior, posteromedial, posterolateral, and composite reach distances.
    b. Independent Variable:
        i. Time since last concussion (months)
    c. Dependent Variable
        i. Anterior reach distance (% of limb length)
        ii. Posteromedial reach distance (% of limb length)
        iii. Posterolateral reach distance (% of limb length)
        iv. Composite reach distance (% of limb length)
4. Are there significant correlations between in firm, foam, and overall BESS errors and the time since last concussion among the concussion history group?
    a. Hypothesis 4: There will not be a significant relationship between time since last concussion and BESS errors among the firm, foam, and overall conditions.
    b. Independent Variable:
        i. Time since last concussion (months)

c. Dependent Variable

1. Firm condition errors
2. Foam Condition errors
3. Overall errors

Operational Definitions

Balance Error Scoring System (BESS): test of static balance using two surfaces (firm and foam) and three stance conditions (single-leg, double-leg, and tandem) in which the clinician counts the numbers of pre-specified errors committed by the participant throughout each 20-second trial (Riemann 1999).

History of concussion: Injury from a blow to the head resulting in a change in mental status, accompanied by one or more of the following symptoms: headache, vomiting, nausea, vertigo, altered balance, fatigue, blurred vision, memory deficits, drowsiness, sleep troubles, and attention deficits (Guskiewicz 2003). History of concussion was classified as a history of one or more concussion.

Time since last concussion: amount of time (in months) between most recent concussion and testing date.

Y Balance Test-Lower Quarter (YBT-LQ): instrumented version of the Star Excursion Balance Test that asks participants to push reach indicator as far as possible with reach foot in the anterior, posteromedial, and posterolateral directions, while maintaining a single-leg stance (Plisky 2009).

YBT-LQ Composite Reach Distance: sum of reach distances from the anterior, posteromedial, and posterolateral reach distances, then normalized to lower limb length.

YBT-LQ Directional Reach Distance: reach distances in the anterior, posteromedial, and posterolateral directions, normalized to limb length.

Limitations

- The forms used for data collection were completed in a self-report format, thus the accuracy may be in question depending on proper recall and willingness to report.
- Performance on the BESS and YBT-LQ may be affected fatigue (Wilkins 2004). Due to the clinical nature of this study, however, it was not feasible to test all athletes at the same time of day or at the same levels of fatigue.
- No lower extremity injury history was gathered for injuries outside of a one year window prior to testing. Previous lower extremity injury may affect YBT scores (Plisky 2009).
- Although control participants were matched by age and sport, it is possible that leg strength and physical condition differed between a participant in the concussion history group and his or her match.

Significance of the Study

With each of the 1.6-3.8 million sport-related concussions experienced each year (Langlois 2006), comes the possibility of long-term symptoms that can affect daily life. This research may help clinicians better understand the effect of concussions on long-term dynamic balance task performance. If we find that athletes with a history of concussion present with poorer dynamic balance performance, this study will complement previous research that suggests that concussion recovery may take longer than traditionally thought and will serve to recommend that the YBT-LQ be explored as a potentially useful concussion evaluation tool.

CHAPTER 2

REVIEW OF LITERATURE

Concussions are a national topic of discussion, specifically concussions that result during sport participation (McCrory 2013). A multifaceted approach to concussion evaluation is often utilized, including balance examinations. Static balance tests are often completed as part of a concussion evaluation, but dynamic balance tasks typically incorporate a movement task to the originally static posture (Winter 1990), however there is little information about the use and applicability of dynamic balance tasks in concussion evaluation, even though they may be more applicable to athletes' postural demands. The purpose of this review of literature is to detail the 1) epidemiology of sport-related concussion; 2) consequences and assessment of concussion; and 3) utility of both static and dynamic balance assessments for concussion evaluation.

Epidemiology of Sport-Related Concussion

It is estimated that approximately 1.6 to 3.8 million concussions occur in athletics occur each year (Langlois 2006), with approximately 21% sustained by high school athletes (Gessel 2007). Concussions account for 8.9% of all high school sport-related injuries (Gessel 2007). In addition, sports are second, only to motor vehicle accidents, as the most common cause of traumatic brain injury in individuals aged 15-24 years (Sosin 1996). Bicycling, football, and playgrounds account for most nonfatal traumatic brain injuries from sports and recreational activities (Gilchrist 2011). The highest overall number of concussions in high school sports results from football (47%), followed by girls' soccer (8%), wrestling (6%), and girls' basketball (nearly 6%) according to a study of 1,936 concussed athletes (Marar 2012). In respect to total injuries in a given sport, concussions account for the highest percentage of overall injuries in boys’ hockey (22%), with girls’ lacrosse (21%), cheerleading (20%), boys’ lacrosse (17%), and football (15%) (Marar 2012). In collegiate athletics, women’s ice hockey has the highest rate of concussions per 1,000 athletic exposures, followed by spring football and men’s ice hockey (Hootman 2007).

Concussions occur more commonly during competition than practice (Gessel 2007). There are more concussions in collegiate athletics than high school sports, however, concussions account for a higher percentage of all injuries in high school athletics (Gessel 2007). In sports played by both males and females (such as basketball), females sustain a higher number of concussions than their male counterparts in both high school and collegiate athletics, particularly in games. (Covassin 2003, Covassin 2003, Gessel 2007). Risk factors for sport concussion include competition, exposure time, type of sport, history of previous concussion, age, female gender, playing position, and technique (Abrahams 2014).

There are three primary mechanisms of concussions: player-to-player contact; player-to-ground contact; and player-to-equipment contact (Marar 2012). Player-to-player contact is the most frequent cause of concussions in sports like football and soccer. Most concussions in sports such as track and field and swimming are caused by player-to-ground contact (ground meaning the playing surface). In lacrosse and softball, most concussions are caused by player-to-equipment contact, such as being struck in the head by a ball, lacrosse stick, or bat (Marar 2012). With three primary mechanisms of sustaining a concussion, concussions can occur in any sport, not just contact sports.

Acute Consequences and Concussion Assessment Protocol

Neurometabolic Cascade Following Concussion

Immediately following a concussion, there is a change in the neuropathology of the brain. Excitatory transmitters, like glutamate, bind to N-methyl-D-aspartate receptors, leading to depolarization of neurons, and a change in the sodium and potassium concentrations. The sodium-potassium (Na^+-K^+) pump is forced to work harder to restore normal function (Giza 2001). To do so, neurons requires a large amount of adenosine triphosphate, resulting in a rapid increase in glucose metabolism. The rapid increase in glucose demand causes a cellular level energy crisis. The abnormal levels of oxygen and glucose consumption, combined with the energy demands cause an increase in overall neuronal glucose consumption, at times as much as 46% above normal that can last from 30 minutes to four hours (Giza 2001, Signoretti 2011). The energy crisis causes the brain to become less capable of handling a second injury. Succeeding the increased glucose consumption by the neurons, the brain enters depressed metabolism. A very large increase in calcium may also occur, worsening the brain's energy situation. The calcium increases can cause oxidative metabolism to halt, causing cell death by activating specific pathways, and impairing neural connectivity (Giza 2001, Signoretti 2011).

Changes in vascular blood flow to the brain also occur immediately following concussion, which is the time frame in which blood flow is needed most (Giza 2001). Concussive injuries produce dysfunction in autoregulation of blood flow in the brain (Lewelt 1980) and can cause overall acute decrease in cerebral blood flow (Yuan 1988, Yamakami 1989). Cerebral blood flow is also reduced in a pediatric population acutely, and, despite normal neurocognitive test scores, remains reduced for 73% of concussed individuals at 14-days post-injury and for 36% at 30-day post-injury (Maugans 2012).

Acute Consequences and Assessment

Concussion assessment and management can vary greatly among clinicians, but often includes a clinical evaluation, self-report of current symptoms, a form of postural stability testing, and a neurocognitive exam (Broglio 2007). The initial evaluation should also include an assessment of cervical spine and cranial nerves (Guskiewicz 2004). If resources allow, baseline exams should be performed with the same measures as post-concussion assessment to establish individualized values as a comparison point for each athlete prior to competition (Notebaert 2005).

There are multiple sideline tools for concussion assessment, including the Standardized Assessment of Concussion, Balance Error Scoring System, and/or symptom checklist (Piland 2003, Notebaert 2005). If concussion is still suspected after sideline assessment, the athlete should be removed from play and undergo more detailed testing using tools such as advanced posturography (discussed in further detail in a later section) or neurocognitive exams once the athlete is asymptomatic (Notebaert 2005, McCrory 2013).

Symptomology

The acute diagnosis of concussion, along with the formation of a return-to-play protocol, involve the self-report of symptoms (McCrory 2013). There are numerous tools used to assess concussion symptoms, one of which is referred to as the Graded Symptom Checklist (Alla 2009). The Graded Symptom Checklist is a 17-21 symptom checklist that uses a 7-point Likert scale to rate possible concussive symptoms (such as headache, dizziness, sleep problems, neck pain, etc.) based on a 0-6 scale, with 0 meaning the symptom is not present, 1 to 2 as mild, 3 to 4 as moderate, and 5 to 6 as severe (Lovell 1998, Guskiewicz 2004, Patel 2007, Alla 2009). The 2012 Consensus Statement on Concussion in Sport reports that signs and symptoms fall into the following clinical domains: somatic, cognitive, and/or emotional. A concussion should be suspected if an athlete reports symptoms from at least one component following a blow to the head, (McCrory 2013). Emotional symptoms are comprised of emotional liability (McCrory 2013). Somatic symptoms can include headache, nausea, and vomiting. Cognitive symptoms include memory loss and trouble thinking (Hunt 2010). Headache is the most common self-reported symptom (86.0-93.4%), followed by dizziness (67.0-74.6%), difficulty concentrating (56.6%), confusion (46.0-59.0%), vision changes (37.5%), nausea (28.9%), drowsiness (26.5%), and amnesia (24.3%), among others (Guskiewicz 2000, Meehan 2010). Symptoms generally resolve within seven days (McCrea 2003), with cognitive function returning to baseline levels within five to seven days, and balance deficits returning to pre-concussion levels within three to five days for a majority of cases (Grindel 2001, McCrea 2003).

Neurocognition

Neurocognitive exams can be computerized or administered using paper-and-pencil. Paper-and-pencil tests, as well as computerized exams, can be comprised of a battery of tests that examine cognitive domains such as concentration, motor function, information processing/speed, visual and verbal memory, executive functioning, reaction time, and visual motor speed (Grindel 2001, Johnson 2011). It has been suggested that a full battery of tests should be used rather than one single exam (Echemendia 2001).

A meta-analysis of the neurocognitive effects of concussion found large deficits in "global cognitive functioning" (a broad term assessing the social, occupational, and psychological functioning of patients (Escorpizo 2011), memory acquisition, and delayed memory within the first 24 hours of recovery (Belanger 2005). In addition, female athletes have significantly greater declines in simple and complex reaction times compared to their preseason baseline levels, while exhibiting post-concussion cognitive impairment 1.7 times more frequently than males (Broshek 2005). In a separate study by Collie et al, athletes who were symptomatic post-concussion displayed statistically significant decreases in cognitive abilities in the tests of motor function and attention, but no significant changes were seen in tests of memory and learning capabilities (Collie 2006). Immediately testing athletes with concussion yielded a significant worsening of scores after head trauma and concussion, compared to baseline scores, indicating the possible presence of concussion (Galetta 2011).

The King-Devick test, an assessment that asks participants to read numbers aloud as quickly as possible, is a visual sideline assessment of neurocognition (Galetta 2011). The King-Devick test is able to assess eye movements, attention, and language. Impaired eye movement has been suggested to signal brain functioning that is not at an optimal level (Heitger 2009).

Balance

Acute deficits in balance may also be present following a concussion (McCrory 2013). Concussed athletes may have trouble processing sensory information from the visual, somatosensory, and vestibular systems (discussed in more detail in a later section), particularly the coordination of the visual and vestibular pathways (Guskiewicz 2001, Hunt 2010). Balance can be tested by numerous tools, two of which, the Sensory Organization Test and Balance Error Scoring System, are discussed in a further section. The Balance Error Scoring System is a commonly-recommended sideline assessment of concussion (McCrory 2013, Broglio 2014).

Return to Play

A return-to-play progression should be started when the athlete is determined to be asymptomatic, presents with no neurocognitive or balance impairments, and has a normal clinical examination (Broglio 2014). A typical return-to-play protocol consists of the following stages: 1) no activity; 2) light aerobic exercise; 3) sport-specific exercise; 4) non-contact training drills; 5) full-contact practice or unrestricted training; and 6) return to play (McCrory 2013). The average time frame between levels is roughly 24 hours, and, typically, an athlete diagnosed with a concussion can expect to miss at least one week of activity (Broglio 2014). If, during a step of the return-to-play program, the patient experiences post-concussion symptoms, the patient should stop that activity, regress to the previous stage, and try the same stage 24 hours later (McCrory 2013, Broglio 2014). No patient should return-to-play on the same day as a concussive injury, (Broglio 2014). Some disagreement exists among clinicians, however, as to the proper return-to-play timeline, particularly due to differences in individual concussion cases (Broglio 2014).

Chronic/Long-Term Consequences of Concussion

Mild Cognitive Impairment and Depression

Previous literature illustrates a possible relationship between concussion history and prevalence of mild cognitive impairment, dementia, and depression (Guskiewicz 2005, Hart 2013, Randolph 2013). Recurrent concussion has been associated with increased incidence of mild cognitive impairment (a precursor to dementia), as well as self-reported memory impairment (Guskiewicz 2005). Retired professional football players with three or more concussions have a fivefold prevalence of mild cognitive impairment and a threefold prevalence of memory deficits compared to retired professional football players with no prior concussions (Guskiewicz 2005). Retired players with three or more concussions also present with incidences of earlier onset of Alzheimer’s and higher rate of depression compared to general population (Guskiewicz 2005, Hart 2013). As mentioned previously, concussions have been suggested to be a structural injury to the brain, and in retired professional football players, those with mild cognitive impairment and/or depression experienced significant changes in cerebral white matter, as well as abnormalities in regional blood flow, particularly increased flow to the left inferior parietal lobe, posterior superior temporal gyrus, bilateral midcingulate gyri, and right middle frontal gyrus (Hart 2013). Recent research has also shown a relationship between concussion histories and incidence of depression; however, most research has been conducted among professional or retired athletes. These studies tend to show a dose response between number of previous concussions and depression rate (Guskiewicz 2007, Kerr 2012, Hart 2013).

Chronic Traumatic Encephalopathy

Over the past few decades, evidence of a neurodegenerative disease known as Chronic Traumatic Encephalopathy has become more prevalent. The premise of Chronic Traumatic Encephalopathy comes from what was described by Mawdsley and Ferguson (1963) as “punch-drunk” in boxers (Mawdsley 1963). The term Chronic Traumatic Encephalopathy originated in 1996 (Miller 1966), and in 2005, Dr. Bennet Omalu published the first evidence of Chronic Traumatic Encephalopathy in a retired professional football player, with the presence of diffuse amyloid plaques, sparse neurofibrillary tangles, and “tau-positive neuritic threads” (Omalu 2005). It is unknown what percentage of concussed and non-concussed athletes develops Chronic Traumatic Encephalopathy, although a lifetime prevalence rate of 3.7% has been suggested (Gavett 2011). In a study of 51 confirmed cases of Chronic Traumatic Encephalopathy, 90% of cases occurred in former athletes, however these studies do not control for exposure to concussion, head impact exposure, and do not include a proper control group (McKee 2009). Chronic Traumatic Encephalopathy usually appears in the middle of life and presents as memory deficits, headaches, violent or aggressive tendencies, gait abnormalities, slurred speech, confusion, and cognitive decline, among others (McKee 2009, Omalu 2010, Gavett 2011). Currently, Chronic Traumatic Encephalopathy can only be diagnosed via post-mortem autopsy, although specialized positron emission tomography scans may make it possible to diagnosis in living individuals (Small 2013). Given the research discussed regarding chronic cognitive impairments and Chronic Traumatic Encephalopathy, it is becoming more and more evident that concussive injuries may be more severe than previously thought.

Balance and Gait Impairments Persisting Beyond Recovery Window

Balance deficits have been seen beyond the acute recovery period in many cases. Slobounov *et al.*, using virtual reality technology, demonstrated balance deficits in multiple studies that were still present 30 days post-concussion (Slobounov 2007, Slobounov 2008)., well beyond the current assumed recovery window (McCrea 2003) and well beyond when asymptomatic athletes are cleared to return-to-play. Balance recovery was even more delayed following recurring concussive episodes (Slobounov 2007). Even at the time of return-to-play, concussed individuals exhibit greater center of pressure velocity than controls during a static balance assessment, particularly in the anterior/posterior direction (Powers 2014). The authors believe this is “due to poor sensorimotor integration of the lateral vestibulospinal tract” following concussion (Powers 2014). Multiple studies (De Beaumont 2011, Sosnoff 2011, Kleffelgaard 2012) as described individually below, have shown long-term (at least 6 months post-concussion) balance abnormalities in individuals with a history of concussion compared to controls using the non-linear measure of approximate entropy, with Sosnoff *et al.* reporting increased anteroposterior sway irregularity and decreased mediolateral sway irregularity compared to individuals that had not sustained a concussion (Sosnoff 2011). Cavanaugh *et al.* determined that athletes with seemingly regular static balance post-concussion still displayed changes in balance using approximate entropy (Cavanaugh 2005). In a sample of asymptomatic football players with an average of 19 months since most recent concussion, the previously concussed group showed worse approximate entropy values in the anteroposterior direction compared to controls, suggesting that they have more sway variability (De Beaumont 2011). In a longitudinal study of previously concussed individuals, 31% of participants self-reported balance deficits remained at four years post-concussion (Kleffelgaard 2012). This growing body of literature suggests that sophisticated laboratory intensive measures of balance reveal residual deficits that persist beyond the time points when clinical recovery is typically considered.

Chronic concussive effects have also been identified using dynamic activities such as gait. In a study of 40 individuals with a history of concussions, Martini *et al*. concluded that those with a history of concussion spent more time in the double-leg stance phase of gait, less time in single-leg support stance, and also had a slower walking velocity, even after 6.3 years post-concussion (Martini 2011). At time of return-to-play, concussed athletes also exhibited increased variability in swing-times, which, in part, lead to less stability and a more conservative gait pattern due to “difficulty controlling temporal characteristics of gait.” (Powers 2014). Other studies report similar results, particularly in dual-task walking, or navigating an obstructed path (Chou 2004, Parker 2005, Parker 2006, Catena 2007, Fait 2013). An attention distraction causes those with a history of concussion to have increased center of mass sway in the frontal plane and increased medio-lateral separation between center-of-mass and center-of-pressure (Chou 2004, Parker 2005, Parker 2006). The increased sway during dual-task gait trials are still present 28 days post-concussion (Parker 2006). Few relationships have been found between neurocognitive test results and gait measures, suggesting differences in recovery time between the variables, with gait variables requiring a longer recovery time (Parker 2007). These studies seem to suggest that concussed athletes exhibit balance deficits that persist well beyond the assumed recovery window (McCrea 2003), which may indicate that current concussion assessment tools are insufficient for assessing motor control adaptations. Gait assessment, however, generally require expensive equipment, usually in a laboratory setting, making it unpractical for clinical use, thus it's exclusion as a measure in this study. It is possible to perform gait analysis using cameras and tape measures, however that method can be time consuming and difficult. A dynamic balance test, such as the Star Excursion Balance Test or YBT-LQ, may be a more viable option due to the cost-effectiveness and the ability to test athletes quickly.

Balance

No single definition for balance exists, but one definition commonly used is "a person's ability to control equilibrium" (Hall 2012). That definition, however, does not necessarily involve human constructs. For humans, the term "postural control" is also often used, as it can be defined as "the act of maintaining, achieving or restoring a state of balance during any posture or activity" (Pollock 2000), with postural control strategies being the methods "used to return the body to equilibrium in a stance position" (Horak 2006). Postural control strategies have been labeled as either reactive or predictive strategies, and a combination of reactive and predictive strategies is also possible (Maki 1997, Pollock 2000).

Balance is regulated by a rather intricate system consisting of the visual, vestibular, and somatosensory systems (Collins 1995). The balance mechanism consists of the following subcomponents that, in ideal situations, work together: biomechanical constraints, movement strategies, orientation in space, control of dynamics, cognitive processing, and sensory strategies (Horak 2006). Biomechanical constraints affecting balance involve the base of support, which incorporates strength, degrees of freedom (often referring to the independent oscillations in movement during static balance), and limits of stability (the area around which a person can shift their center of mass while maintaining balance without the need to move his/her base of support) (Crutchfield 1989, Horak 2006). Two common strategies exist: ankle strategy and hip strategy

(Runge 1999, Horak 2006). The ankle strategy is characterized by body sway resembling a single-segment inverted pendulum about the ankle joint, while the hip strategy resembles a double-segment inverted pendulum divided at the hip (Runge 1999). The hip strategy is often seen with the ankle strategy, since a pure, independent hip strategy is not usually observed in isolation (Runge 1999). Orientation in space is related to the "ability of the body to orient with respect to gravity, the support surface, visual surround and internal references" (Horak 2006). Orientation in space is comprised of perception in space, gravity, verticality, and vision. Control of dynamics refers to the ability to control balance and posture while changing postural position (also called dynamic balance) (Horak 2006). Balance requires that many cognitive processes occur simultaneously and as the difficulty of the postural task increases, the amount of cognitive processing also increases (Teasdale 2001). Three systems are involved in the collection and processing of senses as they pertain to balance: somatosensory, vestibular, and visual.

The somatosensory, or proprioceptive, system is mostly utilized in the maintenance of quiet balance and daily activities. The somatosensory system functions to detect sensory input, such as joint movements (Lephart 1998). Mechanoreceptors are located in the skin, muscle units, bone, and joints (Lephart 1998), and muscle spindles provide the nervous system with details regarding muscle length and contractile velocity, while Golgi tendon organs send afferent information about muscle tension (Gaerlan 2012). Those sensory inputs allow the body to relay joint movement information (Shaffer 2007). The integration of sensorimotor input occurs in the basal ganglia, cerebellum, motor cortex, brain stem and spinal cord (Lephart 1998). Together, these inputs are all responsible for coordinating movement. The basal ganglia area is important in maintaining balance and the cerebellum for integration, control, and smoothing of rapid movements (Biedert 2000). The brain stem assists with processing sensory signals, thus helping to stabilize balance (Biedert 2000). It is proposed that athletes have sensory integration deficits following concussion (Guskiewicz 1996) and previous literature suggests possible sensory adaptations arise in head-injured patients that allow the visual system to compensate for a damaged vestibular system (Mallinson 1998).

The vestibular system receives details about position from the vestibules and semicircular canals of the inner ear. The vestibular organs can be used in three ways. First, the vestibular organs can control eye muscles to fix the eyes on one point when the head shifts. Second, they help regulate posture and keep the body upright (Guskiewicz 1996). Finally, they are involved in the awareness of body position in space. The vestibular signals are mostly involved in slow sway (Dietz 1989).

The visual system is comprised of three parts: central, retinal slip, and ambient vision (Gaerlan 2012). The central system perceives and recognizes objects and their motions (Gaerlan 2012). Retinal slip is used to compensate for body displacement. The ambient visual system is responsible for peripheral vision, and is mostly used in balance and self-motion. The ambient system is most important for maintaining balance, particularly a quiet position (Gaerlan 2012). Balance deficits following concussion are likely the result of ineffective sensory integration, particularly affecting the vestibular and visual systems (Guskiewicz 2001).

Static Balance to Assess Concussion

In the vast majority of literature, standing, or static balance is most commonly discussed, and it is the most common way to assess concussed athletes. Static balance involves the task of keeping the center of gravity safely within the area of the feet, or maintaining a stable posture (Winter 1990, Gribble 2007). There are two common tests of static balance in concussed individuals discussed in the literature: the Sensory Organization Test or the Balance Error Scoring System.

The Sensory Organization Test is considered a static assessment given the definitions of static and dynamic balance discussed separately, however, it should be noted that the Sensory Organization Test has also been referred to as dynamic (Broglio 2009). Therefore, it may be considered semi-dynamic. The Sensory Organization Test is performed on the NeuroCom Smart Balance Master System (NeuroCom International Inc., Clackamas, OR). This system consists of a force measurement system, calculating vertical reaction forces during the exam procedure. The procedure consists of standing as still as possible with feet shoulder width apart for three trials of 20 seconds over the six following conditions: 1) eyes open, 2) eyes closed with a stable platform, 3) sway-referenced vision with stable platform, 4) eyes open with sway-referenced platform, 5) eyes closed with sway-referenced platform, and 6) both sway-referenced vision and platform (Guskiewicz 1997). "Sway-referencing" refers to the tilt of visual surround and/or platform to coincide with the participant's stance, particularly the center of gravity angle. As the center of gravity angle changes, so does the position of the surround or platform. In using sway-referencing, either the visual or somatosensory sensory information are altered, requiring the participant to compensate for the altered inputs (Guskiewicz 1997). The Sensory Organization Test compiles a composite balance score, as well as three ratio scores for the somatosensory, visual, and vestibular systems that correspond to the components of the balance mechanism (Broglio 2007). The Sensory Organization Test has a reliability of 61.9% (Broglio 2007), leading it to be considered as a "gold-standard". When analyzing Sensory Organization Test performance using approximate entropy, a measure of regularity, researchers observed altered balance mechanisms in athletes with a history of concussion compared to non-concussed athletes in a range of 6.4-150.9 months post-concussion (Sosnoff 2011). The NeuroCom Smart Balance System, however, is cost prohibitive in most sports medicine settings, which limits the practicality of using it as a standard, particularly at a high school and collegiate level.

The Balance Error Scoring System is more applicable from a financial standpoint as it only requires the use of a stopwatch and a foam pad. Like the Sensory Organization Test, the Balance Error Scoring System incorporates six conditions of 20 seconds. The conditions are: double leg, single-leg, and tandem performed on both a flat surface and foam surface, with the single-leg stance being performed on the non-dominant leg and the tandem stance with the non-dominant foot behind the dominant foot (Riemann 1999). The examiner asks participants to place their hands on their hips, keeping the head erect and the eyes closed. Testers count the number of "errors" performed during each trial. The outcome variables for BESS are the errors in the firm and foam conditions, which when summed together yield an overall number of errors. An error is defined as any of the following actions: participant opens eyes, moves out of the test position, removes hands from hips, moves hips more than 30 degrees into flexion or abduction, lifts feet, or remains out of set testing position for longer than five seconds. Higher Balance Error Scoring System scores indicated more errors, thus poorer balance performance (Onate 2007, Broglio 2009). Although more cost efficient, the Balance Error Scoring System lacks desired reliability, with an interrater reliability (intraclass correlation coefficient) for total scores found to be 0.57 (Finnoff 2009), and intrarater reliability measured between 0.60-0.74 (McLeod 2006, Finnoff 2009, Hunt 2009). Further, when tested immediately post-concussion, only 36% of concussed individuals present with balance impairments when evaluated with the Balance Error Scoring System, with that percentage decreasing as recovery time increased (McCrea 2005). More recent research, however, has found the Balance Error Scoring System to have moderate to high reliability, but low validity, with the inability to detect balance deficits after the third day of concussion recovery (Murray 2014). Despite being just two of the commonly used measures of static balance, the Sensory Organization Test and Balance Error Scoring System protocols don't involve a fully dynamic aspect. These tests strictly ask participants to remain still and maintain a quiet stance. While the Sensory Organization Test has been labeled as the "gold-standard" of balance assessment, and the Balance Error Scoring System test is also commonly used, for the purpose of concussion testing, static balance assessments have been found to exhibit poor reliability (McCrea 2005, Broglio 2007). These static balance tests are very easily influenced by previous exercise, even moderate intensity (Schneiders 2012), therefore may not be relevant to athletes.

Dynamic Balance

It seems possible that a concussed individual may be able to maintain a quiet stance and not show any balance deficit while performing a static task, but once presented with a perturbation disruption to balance may become more apparent. Dynamic balance can be described as "attempting to maintain a stable base of support while completing a prescribed movement" (Winter 1990). Given the definition, then, it can be derived that many activities seen in daily life and in sports, involve dynamic balance.

Prior research has shown that static balance measures do not adequately reflect the ability of a participant during dynamic balance measures (Karimi 2011), nor accurately demonstrate existing balance deficits as well as dynamic balance tests (Ross 2004), suggesting that dynamic balance is more difficult (Karimi 2011). It seems possible that dynamic balance examinations may be more sensitive to balance deficits later in the concussion recovery process because the tasks require greater motor control and allocation of attention.

The Star Excursion Balance Test is one example of a dynamic balance test. Essentially, participants are asked to stand in a single-leg stance while performing a maximum reach with contralateral limb. Originally, the Star Excursion Balance Test utilized eight reach directions while standing on each foot: medial, anteromedial, anterior, anterolateral, lateral, posterolateral, posterior, and posteromedial, with respect to the stance foot, and also included a rotational motion (Gray 1995). Six practice trials in each direction, followed by three test trials are completed to eliminate a practice effect (Hertel 2000, Plisky 2006). Stance foot is traditionally placed with the center of the foot on the vertex (Hertel 2006). A trial is excluded if a participant fails to maintain the single-leg stance, stance foot moves, touches reach foot with too much pressure, or failed to return to starting position (Plisky 2006). Although commonly done in the eight directions previously mentioned, recent studies have modified the Star Excursion Balance Test to use one to three directions (Hertel 2006, Plisky 2006). Plisky et al. utilized the anterior, posteromedial, and posterolateral directions (Plisky 2006). The lower limb length is also generally measured to normalize reach distances and calculate a composite score (Plisky 2006). The Star Excursion Balance Test is considered very reliable, with interrater reliability ICCs generally ranging from 0.86-0.92, with one study finding an ICC as low as 0.67, and intrarater reliability between 0.76 and 0.96 (Kinzey 1998, Hertel 2000, Gribble 2013).

The Star Excursion Balance Test has been studied as a potential assessment tool for a multitude of purposes, including comparing balance among differing sports, predicting lower extremity injury, and identifying the presence of chronic ankle instability (Olmsted 2002, Bressel 2007, Hubbard 2007, Plisky 2009). There are no existing studies, however, that relate Star Excursion Balance Test scores and concussion history, although some studies have linked dynamic movement deficits and concussion history. Due to the growing body of literature suggesting the presence of post-concussive balance deficits using dynamic balance tasks (Chou 2004, Parker 2005, Parker 2006, Slobounov 2008, Fait 2013, Powers 2014), however, a practical clinical tool is needed for concussion assessment. The Star Excursion Balance Test may be a plausible concussion assessment tool, as well as provide insight into dynamic balance changes post-concussion.

In an effort to simplify the traditional eight-direction Star Excursion Balance Test, researchers identified the anterior, posteromedial directions were most identifiable of Chronic Ankle Instability (Hubbard 2007) and the posterolateral reach demonstrated hip extension strength (Hubbard 2007). The Star Excursion Balance Test was then simplified to a three-direction version, which lead to an instrumented protocol called the Y Balance Test-Lower Quarter™ (YBT-LQ) (FunctionalMovement.com, Danville, VA). The Y Balance Test Kit™ consists of a stance platform and three pieces of PVC pipe attached to the stance platform and extending the anterior, posteromedial, and posterolateral directions with reach indicators attached to all three extensions. There is 135° between the anterior pipe and the posteromedial and posterolateral pipes, and 45° between the PM and PL pipes (Plisky 2009). While barefoot, participants are asked to push the reach indicator in the red target area as far as possible using the reach leg. Trials are discarded and repeated if the participant fails to stay on one foot, kicks or pushes the reach indicator, uses the reach indicator for support, or failed to return to the starting position under control. Participants perform six practice trials in each reach direction on each foot, followed by three test trials, with reaches measured to the nearest half centimeter. Reliability increased using the YBT-LQ compared to the Star Excursion Balance Test, with intrarater reliability as good to excellent (interclass correlation coefficient, ICC:0.85-0.91) and inter-rater reliability as excellent (ICC: 0.99-1.00) (Plisky 2009).

Summary of Rationale for the Study

As previously discussed, sport-related concussions are commonplace in athletics. They have potentially life-changing symptoms, including deficits in balance that may linger for an extended period of time (Slobounov 2008, Sosnoff 2011). Traditionally, those balance deficits have been examined using a static balance assessment, such as the Balance Error Scoring System or the Sensory Organization Test. Individuals recovering from concussions have shown changes in gait, however, with some lasting longer than the traditional seven to ten day recovery window (Parker 2006, Martini 2011). As previously discussed, researchers have shown long-term altered balance mechanisms using approximate entropy and the Sensory Organization Test post-concussion. Although prior research demonstrates that balance deficits resolve quickly following concussion when assessed using static measures, no previous research has examined the long-term effects of sport-related concussion on strictly dynamic balance, nor explored a dynamic balance task as a means of assessing concussion incidence and recovery.

CHAPTER 3

METHODS

Participants

Participants for this study were recruited from an initial pool of 426 Division I collegiate athletes, and were between 18 and 25 years of age. Participants completed testing as part of an existing pre-participation examination. Inclusion was met if participants were active in and met eligibility for intercollegiate athletics. Participants were excluded if they exhibited any of the following: 1) any diagnosis of a vestibular disorder, 2) lower extremity injury/surgery from which participant has not been cleared to return to play, 3) current illness (e.g. head cold, influenza), 4) chronic ankle instability (as defined by a score <24 on the Cumberland Ankle Instability Tool) (Gribble 2014), or 5) under the age of 18. Inclusion and exclusion was determined by self-reporting on a screening questionnaire. Prior to any testing, participants signed an informed consent approved by the Institutional Review Board at the University of Georgia. Control participants were matched along the following criteria: gender, sport, and age (within one year). All but one participant from the concussion history group were able to be matched within the same sport. The remaining participant was matched to a similar type of sport of the same gender. Forty-five participants in each group were analyzed from the following sports: baseball (n=8), men’s basketball (n=8), equestrian (n=10), football (n=16), women’s gymnastics (n=6), women’s soccer (n=11), softball (n=2), track and field (n=20), women’s golf (n=2), men’s tennis (n=4), and women’s volleyball (n=3).

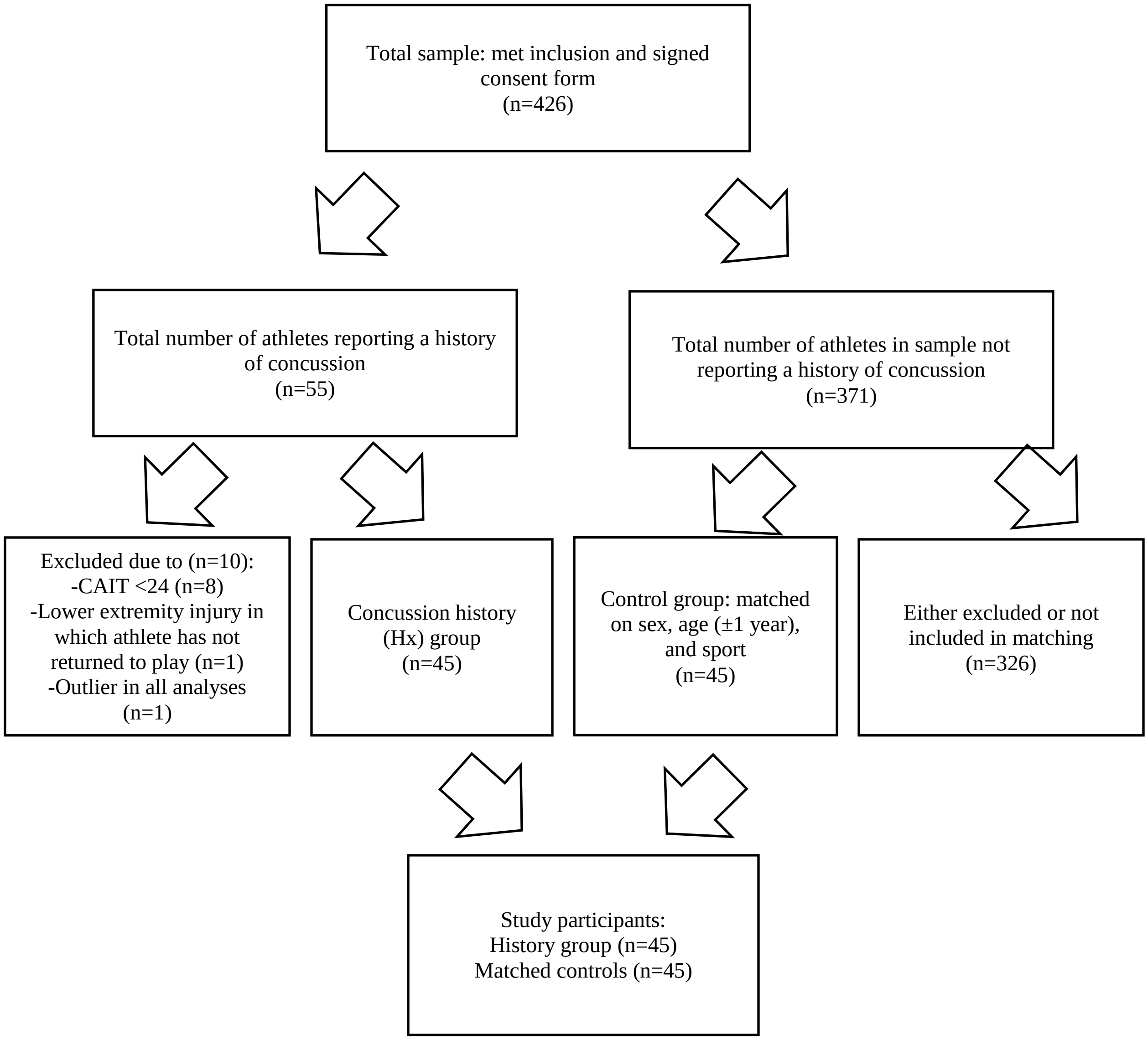

Figure 3.1: Consort diagram for participant selection.

Instrumentation

The test was completed using the Y Balance Test Kit™, with tubes constructed of PVC pipe extending from the stance platform in the anterior (A), posteromedial (PM), and posterolateral (PL) directions to measure the reach distances (Figure 3.1). Distances are denoted and measured on the testing apparatus, and measured to the nearest half centimeter.

The BESS was performed on a firm surface (floor) and foam surface (medium-density foam with a thickness of 10 cm) (Airex AG, Switzerland). An iPad (Apple, Cupertino, CA) was used to record the trials and track the 20 second time frame.

Concussion history was determined via self-report questionnaire based on a concussion questionnaire (Appendix B). Participants reported the number of concussions diagnosed by a medical professional, the approximate date (month and year) of concussion, age at time of injury, whether or not participant experienced a loss of consciousness, whether they experienced either retrograde or anterograde amnesia, and how long symptoms persisted. These questions were then repeated to assess concussions they may have sustained where they experienced symptoms following a blow to the head without seeking medical evaluation. Participants were also administered the Cumberland Ankle Instability Tool (Appendix A) (Hiller 2006) to test for chronic ankle instability. The Cumberland Ankle Instability Tool has been found to have a sensitivity of 0.56 and a specificity of 0.86 (Donahue 2011). Lower limb injury history was also recorded using a self-constructed self-report questionnaire (Appendix C).

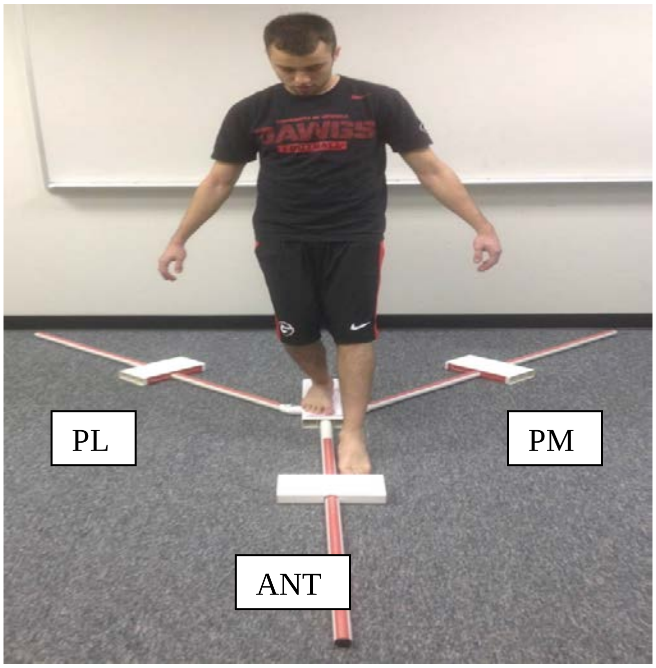

Figure 3.2: YBT-LQ Reach Directions: Right foot reach; Anterior (ANT), Posteromedial (PM), Posterolateral (PL)

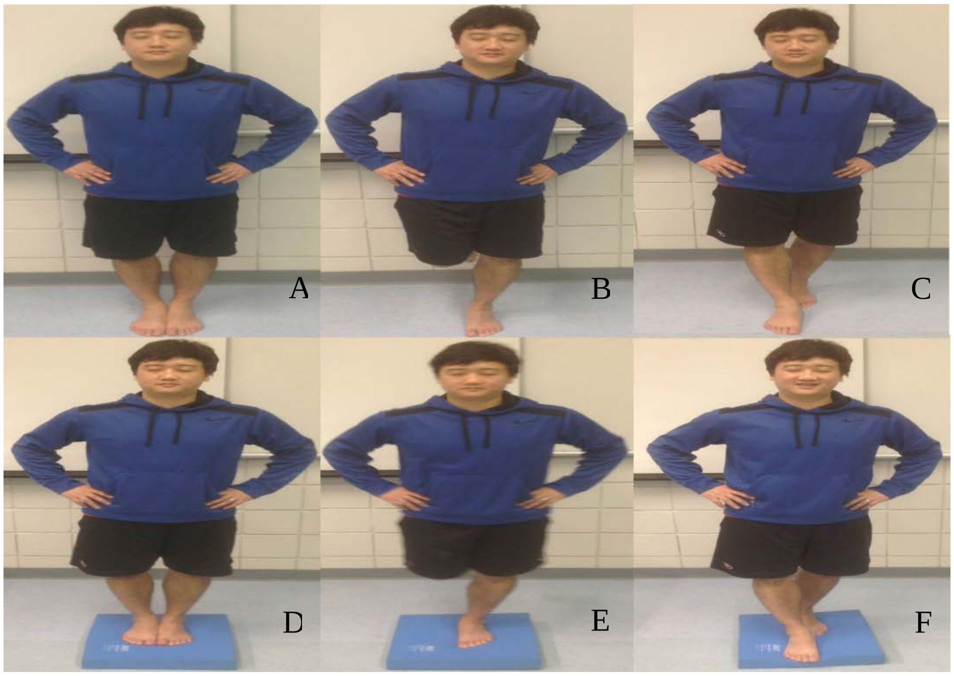

Figure 3.3: BESS Stances: A-C: Firm, D-F: Foam, A/D: Double Leg, B/E: Single Leg, C/F: Tandem

Procedure

Two testers performed an online training course for the YBT-LQ (ybalancetest.com, Danville, VA). Participants received an overview of testing procedures. Participants signed the informed consent form, completed the concussion questionnaire, the Cumberland Ankle Instability Tool, and the Lower Limb Injury Questionnaire. The height, mass, age, gender, dominant leg, and limb lengths of participants were recorded. The dominant limb was defined as the preferred leg used to kick a ball for distance (non-stance limb). Testers were blinded as to whether or not participants had a previous history of concussion.

The reach directions of the YBT-LQ are shown in Figure 3.1. Starting limb and reach direction order were counterbalanced across participants. One of two testers (intraclass correlation coefficient: ICC > 0.90) recorded reach distances by observing how far the reach indicator is pushed (in cm). To perform the YBT-LQ, participants followed the official YBT-LQ protocol. Participants were instructed to stand barefoot on stance platform and place stance foot on center of platform with distal part of toes immediately behind the red line. Participants were asked to push the reach indicator for maximum distance, while pushing in the red reach box on each indicator. Trials were discarded and repeated if the participant:1) failed to stay on one foot, 2) kicked or pushed the reach indicator, 3) used the reach indicator for support/didn't push in red reach box on indicator, and/or 4) failed to return to the starting position under control. Discarded trials were not recorded nor counted. Participants performed six practice trials in each reach direction on each foot, followed by three test trials. Reach distances were measured to the nearest half centimeter. Participants were allowed a maximum of 15 seconds between trials. The YBT-LQ required no more than five minutes per participant. Participants were also asked to lie in a supine position, reset the pelvis by thrusting hips upwards with feet flat, and extending their legs.

The investigator then measured limb length on both lower limbs, using standard clinical cloth tape measurer, as the distance from the most inferior aspect of the ASIS to the most distal portion of the medial malleolus (Hertel 2000). This method of measuring limb length was found to be both valid and reliable, with interrater and intrarater reliability calculated as excellent (ICC ≥0.985) (Neelly 2013).

Participants also underwent the BESS assessment of static balance. For more accurate scoring, tests were video recorded for later error scoring. Participants performed a double-leg, single-leg, and tandem stance on both the firm and foam surfaces, for a total of six conditions. Each trial lasted 20 seconds, as measured by an iPad. In each condition, participants were asked to place their hands on the iliac crests, and told the trial would begin once the participant closes his/her eyes. To perform the double leg stances, participants were instructed to place feet close together, place hands on the iliac crests, and keep eyes closed. For the single-leg stances, participants were instructed to keep the contralateral leg in 20° of hip flexion and 45° of knee flexion (Riemann 1999, Guskiewicz 2001), as well as told to maintain a quiet stance and remain as motionless as possible in the stance position with eyes closed, keeping their hands on their iliac crests. During the tandem stance, the non-dominant leg was placed behind the dominant leg. The dominant leg was defined as the leg used to kick a ball. Participants were instructed to correct themselves and return to testing position, should they lose their balance.

Determination of YBT-LQ and BESS Interrater Reliability

Interrater reliability for the YBT-LQ was determined by two raters testing and scoring 23 volunteers. Volunteers were tested by one of two raters and immediately tested by second rater. Initial rater was alternated, as the rater who tested first for one volunteer was second for the next, etc. Starting reach foot and direction was counterbalanced. All reach distances were measured and recorded by one of two primary testers. Interrater reliability for the BESS was gathered by all three raters independently scoring 12 BESS assessments from recorded videos. Intraclass correlation coefficients were calculated based on those reported scores.

Data Reduction

History of concussion: A participant was classified as having a history of concussion if at least one of the following was reported: 1) one or more concussions diagnosed by a medical professional, and/or 2) one or more incidences of at least one symptom of concussion following a blow to the head. Participants that reported a history of one or more either diagnosed or undiagnosed concussion were assigned to the Concussion History (Hx) group. Matched controls were identified among the remaining participants with no history of concussion.

YBT-LQ Reach Direction Distances: Reach distances were averaged across the three trials for each direction (ANT, PM, PL) and then normalized to limb length by dividing the averaged reach distance (cm) by the participant's limb length (cm), then multiplying that by 100 (Plisky 2009). It is important to note that the official YBT-LQ protocol uses maximum reaches, but we incorporated the averages due to increased test-retest reliability (Shaffer 2013).

(Average ANT Reach Distance/Limb Length)*100

(Average PM Reach Distance/Limb Length)*100

(Average PL Reach Distance/Limb Length)*100

For this study, the Non-Dominant reach distances were analyzed. The non-dominant foot was determined by the foot tested during the BESS testing portion (the dominant foot was defined as the foot used to kick a ball). This was completed to fairly relate the the BESS and YBT-LQ since both are included as analyses.

YBT-LQ Composite Reach Distance: YBT-LQ Composite Scores were calculated by dividing the sum of the average reach distance in the A, PM, and PL directions by 3 times the limb length (LL), which is then multiplied by 100 (Plisky 2009). Again, the official YBT-LQ protocol uses maximum reaches in the calculation of composite scores, however, we used averages due to increased test-retest reliability (Shaffer 2013).

[(Average ANT Reach Distance + Average PM Reach Distance +
Average PL Reach Distance)/Limb Length*3]*100

BESS Errors: Following testing, one of three raters (intraclass correlation coefficient: ICC > 0.85) scored the BESS tests by counting the number of errors committed. An error was defined as any of the following actions: 1) hands lifted off of iliac crests, 2) participant opened eyes, 3) participant stepped, stumbled, or fell out of testing position, 4) participant moved hips more than 30 degrees into flexion or abduction, 5) participant lifted forefoot or heel, or 6) participant remained out of set testing position for longer than five seconds (Riemann 1999, Guskiewicz 2001). Errors committed during the BESS were recorded and the totals for the firm and foam conditions were calculated, as well as the overall number of errors.

Time since most recent concussion: The time since most recent concussion was determined as the number of months since last concussion to the date of testing.

Statistical Analysis

Based on a study examining the effect of concussion history on gait (Martini 2011), a priori power analysis with statistical power=0.80 and $\alpha<0.05$ indicated a necessary sample size of nine participants per group using G*Power software (G*Power, Version 3.1.9.2, Kiel, Germany). Initially, descriptive statistics were analyzed and demographic information compared between groups. We evaluated the YBT-LQ data and excluded any outliers (outliers were be defined as values beyond three standard deviations of the mean). To address research question 1, four separate one-way Analyses of Variance (ANOVAs) were performed to compare the non-dominant (ND) YBT-LQ composite reach distance and ND YBT-LQ reach direction distances (anterior, postermedial, posterolateral) between groups (a priori alpha <0.025 after Bonferonni adjustment for multiple comparisons). To address research questions 2, three separate one-way ANOVAs were performed to compare BESS errors (firm, foam, and overall) between groups (a priori alpha <0.025 after Bonferonni adjustment for multiple comparisons).

To address research question 3, four Pearson's r values were calculated to determine the relationship between time since most recent concussion and ND YBT-LQ scores individual and composite scores reach distances (Table 3.1). To address research question 4, three Pearson's r values were calculated to determine the relationship between time since most recent concussion and BESS firm, foam, and overall errors. The Statistical Package for the Social Sciences 21.0 (SPSS, Inc., Chicago, IL) was used to perform all statistical analyses and calculations.

Table 3.1: Methods of Statistical Analysis

	Research Questions	Data Source	Comparison	Method
RQ1&2	Is there a significant difference in scores between individuals with and without a history of concussions? ***RQ 1) YBT-LQ*** ***RQ 2) BESS***	YBT-LQ: Reach distances in individual directions, limb length BESS: Number of errors committed Concussion history: From self-report questionnaire	IV: Concussion History DV: RQ1) Non-dominant YBT-LQ reach direction (ANT, PM, PL) and composite scores RQ2) BESS errors (firm, foam, overall)	RQ1: Four one-way ANOVAs RQ2: Three one-way ANOVAs
RQ3&4	Is there a significant correlation between scores and the time since the most recent concussion? ***RQ 3) YBT-LQ*** ***RQ 4) BESS***	YBT-LQ: Reach distances in individual directions, limb length BESS: Number of errors committed Time since last concussion: From self-report questionnaire	IV: Time since most recent concussion DV: RQ3) Non-dominant YBT-LQ reach direction (ANT, PM, PL) and composite scores RQ4) BESS errors (firm, foam, overall)	RQ3: Four Pearson's correlations RQ4: Three Pearson's correlations

CHAPTER 4

THE EFFECT OF CONCUSSION HISTORY ON STATIC AND DYNAMIC BALANCE IN COLLEGIATE ATHLETES[1]

[1]Merritt ED, Schmidt JD, Brown CN, Queen RM, Simpson KJ. To be submitted to *Journal of Science and Medicine in Sport.*

Abstract

Objective: To determine if there is a significant difference in static and dynamic balance performance between individuals with and without a history of concussion. **Design:** Cross-sectional. **Method:** Participants included 45 collegiate student-athletes with a history of concussion (Hx) (23 males, 22 females; age=20.0±1.4 years; height=175.8±11.6 cm; mass=76.4±19.2 kg) and 45 matched controls with no history of concussion (23 males, 22 females; age=19.96±1.3 years; height=178.77.6±13.24.8 cm; mass=75.68±18.18 kg). Participants completed the Y Balance Test-Lower Quarter and Balance Error Scoring System. The mean Y Balance Test reach distances were normalized to leg length and a composite score was calculated. Firm, foam, and overall errors were counted during the Balance Error Scoring System. One-way ANOVAs were performed to compare balance performance between groups. Pearson's correlations were performed to determine the relationship between the time since the most recent concussion and balance performance. A priori alpha $\alpha<0.025$ with a Bonferonni adjustment for multiple comparisons was used for all analyses. **Results:** Balance performance did not significantly differ between groups. No significant correlation was found between the time since the most recent concussion and YBT-LQ reach distances or BESS errors. **Conclusion:** Our results suggest that collegiate athletes with a history of concussion do not present with poorer static or dynamic balance when measured using clinically available assessments. The YBT-LQ may still be sensitive to acute balance deficits following concussion. Further research is needed with specific time points following concussion to determine whether dynamic balance differences exist both acutely and chronically following concussion.

Introduction

Concussion is defined as a "brain injury…defined as a complex pathophysiological process affecting the brain, induced by biomechanical forces" (McCrory 2013). Approximately 1.6 to 3.8 million sport-related concussions occur each year resulting in roughly 1.1 million emergency department visit, 235,000 hospitalizations, and 50,000 deaths per year (Langlois 2006). This estimate of overall sport-related concussions may be low, though, due to unreported concussions (McCrea 2004). Recent research has indicated a possible link between concussion history and mild cognitive impairment, self-reported memory impairments, dementia, and depression, among other mental disorders (Guskiewicz 2005, Hart 2013, Randolph 2013). The results of this recent research has caused for concern regarding long-term deficits of concussion.

In order to best manage concussions, sports medicine professionals employ a multifaceted approach including assessments of neurocognitive ability, symptomatology, a clinical exam, and balance testing (McCrory 2013). Baseline assessments are also recommended to provide clinicians with a comparable pre-participation score in the event of a concussion (Broglio 2014). The balance assessments are often tests of static balance using the Sensory Organization Test or the Balance Error Scoring System (BESS) (Guskiewicz 2001, Peterson 2003). Both the Sensory Organization Test and the BESS assess static balance by asking participants to remain still and maintain a quiet stance. Static balance is maintained by the individual making a series of automatic postural adjustments to maintain a quiet stance (Nardone 2010). In addition, static tasks do not involve any purposeful or intentional movement (Lephart 2000). Despite its common usage, the BESS lacks adequate reliability with an interrater reliability (intraclass correlation coefficient) of 0.57 (Finnoff 2009) and intrarater reliability between 0.60-0.74 (McLeod 2006, Finnoff 2009, Hunt 2009). Previous research has shown the

BESS only identified concussion in 36% of participants, when tested immediately following possible concussion, with that percentage decreasing as recovery time increased (McCrea 2005). More recent research has found the BESS to have moderate to high reliability, however, with low sensitivity, being unable to detect balance deficits after the third day of concussion recovery (Murray 2014). In addition, static balance tasks are very easily influenced by previous exercise (Schneiders 2012).

Dynamic balance tasks incorporate postural-kinetic capacity ("ability to develop a counter-perturbation to the postural perturbation induced by the deliberate movement") and sensory-motor integration, two integral pieces of assessing balance capabilities (Nardone 2010). Prior research has shown that static balance measures, in general, do not adequately reflect a participant's ability during dynamic balance measures, possibly suggesting that dynamic balance is more difficult to maintain (Karimi 2011) or at least a separate construct. Also, researchers have found dynamic balance exams to exhibit excellent test-retest reliability, especially when compared to static balance assessments (Schneiders 2012). The Star Excursion Balance Test is an example of a clinically available and commonly used dynamic balance measure. The Star Excursion Balance Test is administered by performing a maximum reach, during unilateral stance, in eight individual reach directions (Olmsted 2002, Plisky 2009). The Star Excursion Balance Test is commonly used as a quick method of assessing dynamic balance (Plisky 2006), possibly indicating its efficacy as a mass-assessment tool. The Star Excursion Balance Test is effective, cost-efficient, and allows for possible detection of balance deficits in clinical populations (Plisky 2006). This 8-direction Star Excursion Balance Test was simplified to a protocol with three directions due to the sensitivity of those directions (Plisky 2009). This test, called the Y Balance Test-Lower Quarter (YBT-LQ), when performed on a commercial apparatus, has increased reliability compared to the Star Excursion Balance Test (Plisky 2009).

Research also shows that individuals present with altered walking kinematics immediately following a concussion (Buckley 2013), and further evidence suggests that concussed individuals present with abnormal gait patterns (Chou 2004, Parker 2005, Parker 2006, Martini 2011, Fait 2013), well after neurocognitive and static balance deficits resolve (McCrea 2002, McCrea 2003). Recent studies have examined long-term balance deficits by using sophisticated measures, such as approximate entropy (Cavanaugh 2005, Sosnoff 2011) and center of pressure data (Powers 2014). These methods, however, are not practical and readily available in most clinical settings, indicating that clinicians lack a widely practical means of assessing for dynamic balance deficits. There is limited research regarding the long-term effects of concussions on athletes, particularly on a clinically-available dynamic balance task. Therefore, a dynamic balance task may be of interest to include in evaluation protocols. This study was a preliminary step in determining if the YBT-LQ is a useful tool for dynamic balance evaluation after concussion.

We pursued to relate previous research utilizing biomechanically intensive gait analyses and current clinical exams by assessing dynamic balance using a clinically available tool. Therefore, the primary purpose of this study was to determine if there is a significant difference in static (BESS) and dynamic (YBT-LQ) balance performance between individuals with and without a history of concussion. The secondary purpose of this study was to determine if there is a significant relationship between both static and dynamic balance performance and times since last concussion.

Methods

Participants for this study were recruited from an initial pool of 426 Division I collegiate athletes, and were between 18 and 25 years of age. Participants completed testing as part of an existing pre-participation examination. Participants met inclusion criterion if they were eligible for and participated in intercollegiate athletics. Participants were excluded if they exhibited any of the following: 1) any diagnosis of a vestibular disorder, 2) lower extremity injury/surgery from which participant has not been cleared to return to play, 3) current illness (e.g. head cold, influenza), 4) chronic ankle instability (as defined by a score <24 on the Cumberland Ankle Instability Tool (Gribble 2014), or 5) under the age of 18. Inclusion and exclusion was determined by self-reporting on a screening questionnaire. Forty-five participants met the inclusion and exclusion criteria to be a part of the concussion history (Hx) group (n=45; 23 males, 22 females; age=20.0±1.4 years; height=175.8±11.6 cm; mass=76.4±19.2 kg) and forty-five subsequent participants met the criteria to be selected to the matched control (Cont) group (n=45; 23 males, 22 females; age=19.9±1.3 years; height=178.7±13.2 cm; mass=75.6±18.1 kg). Controls were selected from the study participant pool matched by gender and sport (all but one was matched by sport), and age (±1 year). The exception was a volleyball player matched to a soccer player. Participants signed an informed consent form approved by the University's Institutional Review Board.

Procedures

Presence of any vestibular or psychological disorder was assessed using a self-reported medical history form in which participants were asked to place a checkmark near any disorder if they have been diagnosed with, including vestibular disorders, learning disorders, etc. The presence of a lower extremity injury was captured by a self-report questionnaire asking participants if they have had any injury in the past year, and if that injury required surgery, if rehabilitation was completed, and if the athlete was cleared to return to play. Concussion history was determined via self-report questionnaire. Participants reported the number of concussions diagnosed by a medical professional, the approximate date (month and year) of concussion, age at time of injury, whether or not they experienced loss of consciousness, whether they experienced either retrograde or anterograde amnesia, and how long symptoms persisted. These questions were then repeated to assess concussions they may have sustained where they experienced symptoms following a blow to the head without seeking medical evaluation. Participants were categorized as having a history of concussion if they reported one or more diagnosed or undiagnosed concussion. The Cumberland Ankle Instability Tool (Hiller 2006) was used to assess the presence or absence of self-perceived chronic ankle instability. Testers were blinded as to whether or not participants had a previous history of concussion.

Static balance was assessed using the BESS. The BESS was performed using a firm and foam surface (Airex AG, Switzerland) while members of the research team captured performance using the iPad (Apple, Cupertino, CA) video recorder and timer. Participants were asked to maintain the testing position for 20 seconds in each of six conditions: double leg, single-leg on non-dominant leg, and tandem stance with non-dominant leg in the back on both a firm and foam surface (Riemann 1999). Leg dominance was determined by asking the participant which foot they would be used to kick a ball for distance. Participants placed their hands on their hips, keeping the head erect, and the eyes closed. Participants were also instructed to correct themselves and return to testing position, should they lose their balance.

Dynamic balance was assessed using the Y Balance Test Kit™ (Functional Movement Systems, Inc., Chatham, VA), comprised of a stance platform and three pieces of PVC pipe attached to the stance platform. The pipes extended in the anterior (ANT), posteromedial (PM), and posterolateral (PL) directions with reach indicators attached to all three extensions (Figure 3.1). There are 135° between the anterior pipe and the posteromedial and posterolateral pipes, and 45° between the posteromedial and posterolateral pipes (Plisky 2009). To perform the YBT-LQ, participants followed the official YBT-LQ protocol (Functional Movement Systems, Inc., Chatham, VA). One of two certified administrators with excellent inter-rater reliability (ICC: >0.90) gave instructions and recorded all measurements. Interrater reliability was determined by two raters testing and scoring 23 volunteers. Volunteers were tested by one of two raters and immediately tested by second rater. Initial rater was alternated, and starting reach foot and direction was counterbalanced. Participants were instructed to stand barefoot on the stance platform and place stance foot on center of platform with distal part of toes immediately behind the red line. Participants were asked to place their foot in the red reach box and push the reach indicator for maximum distance. Trials were repeated if the participant:1) failed to stay on one foot, 2) kicked or pushed the reach indicator, 3) used the reach indicator for support or didn't push in red box, or 4) failed to return to the starting position under control. Participants performed six practice trials in each reach direction on each foot, followed by three test trials. The YBT-LQ start foot and reach direction were counterbalanced. Reaches were measured to the nearest half centimeter (Plisky 2009). Limb length was measured by having participants lie in a supine position, reset the pelvis by thrusting hips upwards with feet flat, and extending the participant's legs. The administrator measured limb length on both lower limbs as the distance from the most inferior aspect of the ASIS to the most distal portion of the medial malleolus (Hertel 2000).

Data Reduction

One of three raters with excellent inter-rater reliability (intraclass correlation coefficient: ICC >0.85) reviewed the videos and scored the BESS errors (Interrater reliability for the BESS was gathered by all three raters independently scoring 12 BESS assessments from recorded videos. ICCs were calculated based on those reported scores.). An error was counted if any of the following occurred: 1) hands lifted off of iliac crests, 2) participant opened eyes, 3) participant stepped, stumbled, or fell out of testing position, 4) participant moved hips more than 30 degrees into flexion or abduction, 5) participant lifted forefoot or heel, or 6) participant remained out of set testing position for longer than five seconds (Riemann 1999, Guskiewicz 2001). BESS errors were counted, and scores were calculated for the firm and foam conditions, as well as a total score. The composite YBT-LQ score was calculated using the equation: [(Average ANT Reach Distance + Average PM Reach Distance + Average PL Reach Distance)/Limb Length*3]*100 (Plisky 2009, Shaffer 2013). Time since last concussion was determined as the number of months since the most recent concussion, as reported on the concussion history questionnaire. Since the BESS assesses the non-dominant limb (ND), the non-dominant YBT-LQ reach distances were analyzed in order to allow for effective comparisons of results.

Statistical Analysis

To compare groups, seven one-way analyses of variance (ANOVA) were performed to compare BESS (firm, foam, total) and YBT-LQ (ANT, PM, PL, Composite) scores between Hx and Cont groups.

Pearson's correlation coefficients were calculated to determine relationship between time since most recent concussion BESS (firm, foam, total) and YBT-LQ (ANT, PM, PL, Composite) scores among the Hx group (n=42 - three participants did not report the date of most recent concussion). A priori alpha $\alpha<0.025$, after a Bonferonni adjustment for multiple comparisons, was used for statistical significance.

Results

No significant differences existed between the Hx and Cont groups in any of the ND YBT-LQ directional or composite reach distances (Table 4.1). Additionally, we did not observe any significant differences between groups in any of the BESS variables (Table 4.2). No significant correlations were found between the time since most recent concussion (mean=47.0±41.3 months, range=2-166 months) and the ND YBT-LQ variables or the BESS conditions (Table 4.2).

Table 4.1: Non-dominant Y Balance Test-Lower Quarter and BESS Scores between Groups

	Hx Mean±SD (95%CI)	Cont Mean±SD (95%CI)	F, p	Cohen's d
YBT-LQ Reach (%LL)				
ANT	66.8±5.9 (65.0,68.5)	66.1±6.9 (64.0,68.1)	F=0.28, p=0.599	0.11
PM	108.0±12.6 (104.1,111.8)	106.5±8.8 (103.9,109.1)	F=0.39, p=0.536	0.14
PL	102.4±12.9 (94.5, 106.2)	101.3±11.2 (98.0, 104.7)	F=0.16, p=0.691	0.09
Composite	92.4±9.0 (89.7, 95.1)	91.3±7.7 (89.0, 93.6)	F=0.34, p=0.559	0.13
BESS Errors				
Firm	2.8±2.3 (2.1, 3.5)	3.6±2.6 (2.9, 4.4)	F=2.44, p=0.122	0.33
Foam	9.1±2.8 (8.3, 10.0)	9.3±2.7 (8.5, 10.1)	F=0.14, p=0.705	0.07
Total	11.9±4.4 (10.6, 13.2)	13.0±4.5 (11.6, 14.3)	F=1.24, p=0.269	0.25

Table 4.2: Pearson's correlation coefficients between months since most recent concussion and Non-dominant Y Balance Test-Lower Quarter reach distances and Balance Error Scoring System errors.

	Correlation (*r*)	**p**
YBT-LQ Reach		
ANT	-0.03	0.867
PM	0.06	0.706
PL	0.09	0.567
Composite	0.07	0.685
BESS Errors		
Firm	-0.11	0.488
Foam	-0.14	0.382
Total	-0.15	0.348

Discussion

Our findings suggest that no differences exist between those with a history of concussion and healthy controls in the anterior, posteromedial, posterolateral, or composite reach distances of the Y Balance Test-Lower Quarter or in the number of errors committed in the firm or foam conditions during the Balance Error Scoring System. We also observed that no significant correlations existed between the amount of time since the most recent concussion and both static and dynamic balance performance. To our knowledge, this is the first study to analyze the effect of concussion history on a clinically available dynamic balance assessment.

Balance testing is a common aspect of concussion assessment, and the acute effects of concussion on static balance are well understood (Guskiewicz 2001, McCrea 2003). Most evidence for this acute effect, however, places a particular emphasis on static balance assessments, such as the Sensory Organization Test and the Balance Error Scoring System. Although acute deficits in static balance are good indicators during initial injury assessment, limited research suggests long-term deficits in static balance using clinically-available measures. There has been an emergence of research suggesting long-term deficits from concussion by using approximate entropy (Cavanaugh 2005, Sosnoff 2011) and center of pressure (Powers 2014) through the Sensory Organization Test or other similar static balance assessment. The results of those previous studies suggest that, although not detectable by a standard static balance measure, true long-term deficits in static balance do exist and may be captured by a more difficult assessment. Using a clinically available tool, however, we found that a history of concussion does not lead to poorer long-term static balance. The lack of significant differences in the current study may be attributed to not evaluating balance using more sophisticated measures used in previous studies.

The results of the current study conflict with previous research regarding dynamic balance, as we found that individuals with a history of concussion do not present with poorer dynamic balance performance. Previous research has examined long-term effects of concussion on gait (Chou 2004, Parker 2007, Martini 2011). Martini et al., found that persons with a history of concussion adapt with a more conservative gait strategy (Martini 2011). The researchers utilized a battery of gait assessments and single and dual-task conditions. Parker et al. (Parker 2007) compared a gait walking assessment and neurocognitive scores and concluded that dynamic motor tasks require a longer recovery time than cognitive measures, with a final time point of 28 months post-injury. Given the results of these studies, it can be deduced that dynamic balance may be still be affected longer than the traditional recovery window, however, no study has found similar results using clinically-available assessments, such as the Y Balance Test-Lower Quarter. We sought to bridge the gap between previous research utilizing biomechanically intensive gait analyses and current clinical practice by examining dynamic balance using a clinically available and widely used assessment tool. However, we may have not seen similar results due to the sensitivity of the YBT-LQ to prolonged deficits in dynamic balance following concussion, or possibly due to the lack of control for time since previous concussion, as the mean time since the most recent concussion was 47.0 months and was variable among our participants.

Although the present study found no significant differences in static and dynamic balance performance between the concussion history group and the control group, differences may still exist and should be further studied. This study analyzed scores from a non-specific time point of previous concussion. This may be of importance as many studies examine participants' balance abilities at time points that are much more recent. Future research should determine whether the

YBT-LQ is sensitive to prolonged dynamic balance deficits at time points closer to the date of concussion. The current study also found no significant correlation between the YBT-LQ reach distances or BESS errors and the time since the most recent concussion. However, with an unspecified time point, these results could be affected by long time periods between previous concussion and testing, demonstrating that athletes with a general history of concussion do not present with dynamic balance impairments, which could indicate recovery. The forms used for data collection were completed in a self-report format, thus the accuracy may be in question depending on proper recall and willingness to report. Performance on the BESS and YBT-LQ may have been affected by fatigue (Wilkins 2004).

Though a post-hoc power analysis would yield rather small power values, we believe this to be a result of very small effect sizes rather than an inadequate sample size. With very small differences in means, along with moderate standard deviations, effect sizes were small, which inherently decreases power.

Given the results of the current study, collegiate athletes with a history of concussion do not present with deficits in static or dynamic balance performance when assessed with clinically available tools, such as the Balance Error Scoring System and the Y Balance Test-Lower Quarter. In addition, in participants with a history of concussion, the time since the most recent concussion is not significantly correlated with static or dynamic balance. Future research should perform similar analyses at more acute time points following concussion, and may also want to utilize a wider participant pool. Future research should also examine the possible presence of asymmetries and the degree of variability in YBT-LQ reach distances between groups.

CHAPTER 5

SUMMARY

This study served two main purposes. The primary purpose of this study was to determine if there is a significant difference in dynamic balance performance between individuals with and without a history of concussion using the YBT-LQ (RQ1). Another primary purpose was to determine if there is a significant difference in static balance performance between individuals with and without a history of concussion using the BESS (RQ2). The secondary purpose of this study was to determine if there is a significant relationship between dynamic and static (RQ3 & RQ4) balance performance and time since last concussion. No significant differences or relationships existed, indicating that athletes with a history of concussion recover from any balance deficits. Future research should examine similar relationships using specific time points of concussion recovery. The primary purposes of this study were to determine if: there was a significant difference in dynamic balance performance between individuals with and without a history of concussion using the YBT-LQ, and if there was a significant difference in static balance performance between individuals with and without a history of concussion using the BESS. The secondary purpose of this study was to determine if there was a significant relationship between static and dynamic balance performance and time since last concussion.

Research Questions 1 and 2

The first hypothesis was that the concussion history group would have significantly shorter anterior, posteromedial, posterolateral, and composite reach distances on the YBT-LQ than the control group. We found no significant differences in non-dominant YBT-LQ scores between groups, indicating that clinical dynamic balance deficits do not exist in athletes with a general history of concussion. The second hypothesis was that the concussion history group would not have significantly more errors among the firm, foam, and overall conditions of the BESS than the control group. We found no significant differences in BESS scores between groups, indicating that clinical static balance deficits do not exist in athletes with a general history of concussion. The effect sizes for RQ 1 and 2 ranged from <0.1-0.3, indicating small to medium effect sizes. It is interesting to note that when compared to recently published YBT-LQ scores of collegiate athletes from multiple sports, the composite scores (mean=91.3%LL for the control group) from the current study were much lower than composite scores (mean=101.2%LL for uninjured athletes) published by Smith et al. (2015) (Smith 2015).

The results from our study contradict previous research that has examined long-term effects of concussion on dynamic balance by analyzing gait (Chou 2004, Parker 2007, Martini 2011). Martini et al., found that persons with a history of concussion adapt with a more conservative gait strategy (Martini 2011). Parker et al. (Parker 2007) compared a gait walking assessment and neurocognitive scores and concluded that dynamic motor tasks require a longer recovery time than cognitive measures. The results for RQ1 allow us to accept the null hypothesis, however, we can reject the null for RQ2.

Our results also dispute previous research that found long-term deficits from concussion by using sophisticated measures, such as approximate entropy (Cavanaugh 2005, Sosnoff 2011) and center of pressure (Powers 2014) through the Sensory Organization Test.

Research Questions 3 and 4

The third hypothesis was that there would be a significant positive relationship between time since last concussion and YBT-LQ anterior, posteromedial, posterolateral, and composite reach distances. We found no significant relationship between the time since last concussion and YBT-LQ reach distances. The fourth hypothesis was that there would not be a significant relationship between time since last concussion. We found no significant relationship between the time since the most recent concussion and BESS errors among the firm, foam, and overall conditions. The results for RQ3 allow us to accept the null hypothesis, however, we can reject the null for RQ4.

Limitations and Future Research

This study was not without limitations. The forms used for data collection were completed in a self-report format, thus the accuracy may be in question depending on proper recall and willingness to report. Performance on the BESS and YBT-LQ may be affected by fatigue (Wilkins 2004). Due to the clinical nature of this study, however, it was not feasible to test all athletes at the same time of day or at the same levels of fatigue. No lower extremity injury history was gathered for injuries outside of a one year window prior to testing. Previous lower extremity injury may affect YBT scores (Plisky 2009). Although control participants were matched by age and sport, it is possible that leg strength and physical condition differed between a participant in the concussion history group and his or her match.

Future research should perform similar assessments analyses at specific time points of concussion recovery, both acutely and chronically, and should expand the number of participants, as well as the participant pool, as this study may not be apply to differing populations. Future research would be well served to evaluate other clinically available assessments, possibly gait analysis, and compare results to more sophisticated measures. Future research should also examine the possible presence of asymmetries and the degree of variability in YBT-LQ reach distances between groups.

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APPENDIX A

Cumberland Ankle Instability Tool Questionnaire

CUMBERLAND ANKLE INSTABILITY TOOL

Please mark the ONE statement in EACH question that BEST describes your ankles. Participant ID ______________

	Left	Right
1. I have pain in my ankle		
Never	☐	☐
During sport	☐	☐
Running on uneven surfaces	☐	☐
Running on level surfaces	☐	☐
Walking on uneven surfaces	☐	☐
Walking on level surfaces	☐	☐
2. My ankle feels UNSTABLE		
Never	☐	☐
Sometimes during sport (not every time)	☐	☐
Frequently during sport (every time)	☐	☐
Sometimes during daily activity	☐	☐
Frequently during daily activity	☐	☐
3. When I make SHARP cuts, my ankle feels UNSTABLE		
Never	☐	☐
Sometimes when running	☐	☐
Often when running	☐	☐
When walking	☐	☐
4. When going down the stairs, my ankle feels UNSTABLE		
Never	☐	☐
If I go fast	☐	☐
Occasionally	☐	☐
Always	☐	☐
5. My ankle feels UNSTABLE when standing on ONE leg		
Never	☐	☐
On the ball of my foot	☐	☐
With my foot flat	☐	☐
6. My ankle feels UNSTABLE when		
Never	☐	☐
I hop from side to side	☐	☐
I hop in one spot	☐	☐
When I jump	☐	☐
7. My ankle feels UNSTABLE when		
Never	☐	☐
I run on uneven surfaces	☐	☐
I jog on uneven surfaces	☐	☐
I walk on uneven surfaces	☐	☐
I walk on a flat surface	☐	☐
8. TYPICALLY, when I start to roll over (or "twist") my ankle, I can stop it		
Immediately	☐	☐
Often	☐	☐
Sometimes	☐	☐
Never	☐	☐
I have never rolled over on my ankle	☐	☐
9. After a TYPICAL incident of my ankle rolling over, my ankle returns to "normal"		
Almost immediately	☐	☐
Less than one day	☐	☐
1-2 days	☐	☐
More than 2 days	☐	☐
I have never rolled over on my ankle	☐	☐

APPENDIX B

Concussion History Questionnaire

CONCUSSION HISTORY

Have you ever been **told or diagnosed** by a medical professional (e.g. Doctor, Athletic Trainer, EMT, Nurse, etc) that you have had a *sport or non-sport related concussion*? ☐Yes ☐No

If Yes, how many are sport related___________, non-sport related _________ and complete the table below.

	Approximate date of injury (mm/yyyy)	Age at time of injury	Did you lose consciousness (i.e. knocked out/blacked out)?	How long were you unconsciousness (seconds)?	Did/do you have difficulty remembering things before or after the injury?	How many minutes do you not remember (min)	How many days did you experience symptoms related to the injury?
Injury #1	_____/_______		☐Yes ☐No	_________(sec)	☐Yes ☐No	_______(min)	________(days)
Injury #2	_____/_______		☐Yes ☐No	_________(sec)	☐Yes ☐No	_______(min)	________(days)
Injury #3	_____/_______		☐Yes ☐No	_________(sec)	☐Yes ☐No	_______(min)	________(days)
Injury #4	_____/_______		☐Yes ☐No	_________(sec)	☐Yes ☐No	_______(min)	________(days)
Injury #5	_____/_______		☐Yes ☐No	_________(sec)	☐Yes ☐No	_______(min)	________(days)

Definition of concussion: A *change in brain function following a force to the head, which may be accompanied by temporary loss of consciousness, but is identified in awake individuals with measures of neurologic and cognitive dysfunction.* Common concussion symptoms include:

- Headache
- Difficulty concentrating or focusing
- Feeling slowed down
- Dizziness, balance problems, loss of balance
- Nausea
- Fatigue/lack of energy
- Feeling in a fog
- Irritable
- Drowsiness
- Forgetting things (before or after the injury)
- Sensitivity to light/noise
- Blurred vision

IMPORTANT: A) you can have a concussion without being "knocked out" or unconscious B) getting your "bell rung" and "clearing the cobwebs" is a concussion.

Following a blow to the head, have you ever experienced any of the symptoms listed above or had a *sport or non-sport related concussion* that **was not evaluated** by a medical professional (e.g. Doctor, Athletic Trainer, EMT, Nurse, etc)?
☐Yes ☐No

If Yes, how many are sport related___________, non-sport related _________ and complete the table below.

	Approximate date of injury (mm/yyyy)	Age at time of injury	Did you lose consciousness (i.e. knocked out/blacked out)?	How long were you unconsciousness (seconds)?	Did/do you have difficulty remembering things before or after the injury?	How many minutes do you not remember (min)	How many days did you experience symptoms related to the injury?
Injury #1	_____/_______		☐Yes ☐No	_________(sec)	☐Yes ☐No	_______(min)	________(days)
Injury #2	_____/_______		☐Yes ☐No	_________(sec)	☐Yes ☐No	_______(min)	________(days)
Injury #3	_____/_______		☐Yes ☐No	_________(sec)	☐Yes ☐No	_______(min)	________(days)
Injury #4	_____/_______		☐Yes ☐No	_________(sec)	☐Yes ☐No	_______(min)	________(days)
Injury #5	_____/_______		☐Yes ☐No	_________(sec)	☐Yes ☐No	_______(min)	________(days)

APPENDIX C

Lower Limb Injury Questionnaire

Subject ID: ___________________

Lower Limb Injury Questionnaire

In the past year, have you had any injury to your lower limbs? ☐ Yes ☐ No

If so,: please describe where the injury occurred (i.e. foot, ankle, shin, knee, thigh, hip)?____

What type of injury? ____

Approximate date of injury: ___________________

Did it require surgery? ☐ Yes ☐ No

If so, approximate date of surgery: ___________________

Have you completed rehabilitation for this injury? ☐ Yes ☐ No

Are you currently completing rehabilitation for this injury? ☐ Yes ☐ No

Are you currently experiencing any pain or other symptoms from this injury? ☐ Yes ☐ No

Have you been returned to full participation in your sport? ☐ Yes ☐ No

Please complete another copy of this form for each subsequent lower limb injury you have sustained within the past year.