SCHLEICH, KRISTEN N., M.S. Postural Control Differences Among Collision, Contact, and Non-Contact Sport Female Athletes (2017).
Directed by Dr. Christopher K. Rhea. 67 pp.

Postural control is defined as the act of maintaining balance, which is a foundational skill in nearly every sport. Postural control can be enhanced with practice or degraded following a neurological insult. Since balance tests are a standard practice to assess neuromotor dysfunction following a suspected concussion, understanding how postural control is affected across different sports that emphasize different skills and have different probabilities of neurological insult from head trauma would help determine whether sport specificity needs to be taken into account within concussion management. In a first step to determine whether differences exist in postural control in relation to sport, adult females actively participating in a variety of sports will be recruited. This study was focused on female athletes for the follow reasons: (1) females are underrepresented in the concussion literature, (2) females experience concussions at a higher rate than males, and (3) concussion symptoms are stronger and last longer in female athletes. Thus, focusing on female athletes helped to close a critical gap in the literature relative to female postural control and concussion management. The purpose of this study was to determine the extent to which postural control in female athletes differs between four distinct sports. The dependent variables were derived from center of pressure (CoP) profiles recorded during three 20 second static stance tasks on a force plate with eyes closed. The average path length of the CoP displacement time series was examined. Further, the CoP displacement time series were differentiated into a CoP

velocity time series and three variables were derived: (1) the average (velocity mean), the magnitude of the variability (velocity standard deviation), and structure of the variability (velocity sample entropy). Poorer postural control was defined as greater CoP movement (increased displacement path length), greater CoP rate of movement (increased velocity mean), greater magnitude in the variation of the CoP rate of movement (increased velocity standard deviation), and less complexity in the variation of the CoP rate of movement (decreased velocity sample entropy). It was hypothesized that the poorest postural control would be exhibited in the sports with the most potential for head trauma. To address this hypothesis, a one-way ANOVA was used to determine if athletes in each sport exhibit different postural control. A main effect for sample entropy was observed, $F(3, 84) = 6.3$, $p = < .001$, $\eta_p^2 = 0.18$, and Bonferroni-corrected follow-up *t*-tests showed that basketball sports had higher sample entropy than football, roller derby, and running sports ($p < .001$). No differences were observed between sports in path length and COP velocity SD. A statistically significant positive correlation was observed in the COP velocity SD of basketball athletes with concussion history ($r = .67$, $p > .05$). These findings indicate that females in different sports exhibit different postural control strategies, which could be due to the balance skills required for their sport and/or the potential for head trauma. This study helps to start filling in the gaps of literature to better understand postural control in female athletes participating in a variety of sports and who are older than athlete cohorts typically studied within the concussion space.

POSTURAL CONTROL DIFFERENCES AMONG COLLISION, CONTACT, AND NON-CONTACT SPORT FEMALE ATHLETES

by

Kristen N. Schleich

A Thesis Submitted to
the Faculty of The Graduate School at
The University of North Carolina at Greensboro
in Partial Fulfillment
of the Requirements for the Degree
Master of Science

Greensboro
2017

Approved by

____
Committee Chair

APPROVAL PAGE

This thesis written by Kristen N. Schleich has been approved by the following committee of the Faculty of The Graduate School at The University of North Carolina at Greensboro.

Committee Chair_______________________________

Committee Members_______________________________

____

____

____
Date of Acceptance by Committee

____
Date of Final Oral Examination

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

CHAPTER I

INTRODUCTION

Postural control is an umbrella term encompassing the act of maintaining, achieving, or restoring a state of balance during any posture or activity (Pallock, Durward, Rowe, & Paul, 2000). Balance is defined as maintaining the body's center of mass (COM) within the base of support (BOS), relying on continuous feedback from various systems within the body to execute appropriate actions (Guskiewicz, 2011; Hrysomallis, 2011). Maintaining balance is critical for achieving activities of daily living, as well as for activities in sports (Lamoth, van Lummel, & Beek, 2009). To help maintain balance, the body naturally exhibits postural sway, a distinct pattern of proactive and reactive behavior happening within the body when gravity (or other external forces) deviates the COM from its previous position. In order to maintain balance, the COM must stay within the BOS—defined as the area in contact with the ground. To counteract gravity or other external forces, the feet push against the ground in the opposite direction in which the COM is moving, causing the COM rotate in the counter direction and to stay within the BOS. These adjustments characterize postural sway, which can be quantified through a variety of variables. One of the most common variables of interest is the center of pressure (COP), which is the location within the BOS of the average pressure exerted by the feet on the ground. By measuring the COP profile over time, postural control can be characterized and used to identify postural instability by looking at movement patterns as the body naturally attempts to keep the COM within the BOS (R. van Emmerik, 2002).

Since postural control relies on sensory integration to maintain balance, a deprivation of sensory information due to head trauma has been shown to affect postural control (Nelson, Janecek, & McCrea, 2013; Noble & Hesdorffer, 2013). Thus, balance tasks have widely been used in the assessment and management of concussions stemming from sport participation, of which the concussion incidence probability varies with sport type. Sport can be categorized into three main types: (1) collision sports such as football, rugby and roller derby, (2) contact sports such as soccer and basketball, and (3) and non-contact sports such as running and tennis. The separation of these three categories is based upon contact physical contact exposure, that is, how likely an athlete is going to come into direct contact with another player, equipment, or surface during play (American Academy of Pediatrics, 2001). The NCAA has suggested that concussion rates are largely dependent on contact and exposure, so the more likely an athlete is to experience impact, the higher the risk for a concussion (NCAA, 2013). It is important to note that exposure refers to head trauma that may or may not have resulted in a concussion. The majority of head trauma exposures do not lead to a concussion, but research suggests that the additive effect of sub-concussive hits to the head can lead to altered neural connectivity in the brain (Abbas, Poole, Breedlove, Leverenz, & Nauman, 2015) and decreased postural control (Gysland et al., 2012). Thus, it is important to determine if postural control characteristics vary between sport type so that accurate baseline databases can be developed as necessary to aid in concussion management.

Furthermore, literature is starting to suggest that the postural control of athletes may differ based on sport specificity, meaning that an athlete's natural corrective patterns during practice and play may be specific to that sport (Bressel, Yonker, Kras, & Heath, 2007; Kiers, van Dieen, Wittink, & Vanhees, 2013; Zemkova, 2014). Different sports naturally place different biomechanical demands on the proprioceptive and somatosensory system, which in turn may affect different balance maintenance characteristics between different athletes. This question can be addressed by examining different sports that fall within sport type categories so that contact and exposure rates are controlled for while varying the sport-specific skills within each sport type category. Deliberate practice is known to influence sport-specific skill development, so the frequency, intensity, and duration of deliberate practice for each athlete will be measured in this thesis (Kiers et al., 2013; Paillard & Zemkova, 2014; Stergiou & Decker, 2011).

The purpose of this study was to determine the extent to which postural control in female athletes may differ between four distinct sports. This study focused on female athletes for the follow reasons: (1) females are underrepresented in the concussion literature, (2) females experience concussions at a higher rate than males, and (3) concussion symptoms are stronger and last longer in female athletes. Thus, focusing on female athletes helped close a critical gap in the literature relative to female postural control and concussion management.). It was hypothesized that the poorest postural control would be exhibited in the sports with the most potential for head trauma.

CHAPTER II

REVIEW OF THE LITERATURE

Concussion: Epidemiology and Pathology

Concussions are defined by the Center for Disease Control (CDC) as a type of traumatic brain injury (TBI) caused by a jolt, blow, or bump to the head causing the brain to rapidly move back and forth (Center for Disease Control, 2015). A standard research definition is similar, defining a concussion as a complex pathophysiological process affecting the brain, caused by traumatic forces to the body, typically rapid acceleration/ deceleration including linear, translational, and rotational forces (Blennow, Hardy, & Zetterberg, 2012; Noble & Hesdorffer, 2013) . Medical providers and researchers currently describe a concussion as a mild brain injury because they are typically not life-threatening and cause no loss of consciousness (Blennow et al., 2012). Concussions typically occur from player-to-player contact, yet contact from equipment and a surface also contribute to many concussive events (Zuckerman, Kerr, Yengo-Kahn, Wasserman, & Covassin, 2015). When the brain suffers a jolt or sudden movement, tiny lesions or tears in the hemispheres occur resulting in other symptoms such as dizziness, nausea, headaches, and dysfunction in complex cognitive functioning, including reductions in mental speed, concentration, and overall cognitive efficiency (Blennow et al., 2012; Kolb & Whishaw, 2014). Neuroscientists have found that a temporary, but complex cascade of neurometabolic processes happens following a concussion effecting brain function for days to weeks post-injury (Giza & Hovda, 2001; Kolb & Whishaw, 2014).The brain is described as plastic, meaning it is constantly changing, creating, and reorganizing neural networks, and these changes can lead to behavioral changes (Giza & Hovda, 2001; Kolb & Whishaw, 2014). The primary function of the brain is to produce behavior, but behavior is not static. When networks of neurons change due to head trauma, behavior also changes. In essence, to alter behavior in some way, the brain structure and/or function may have changed (Kolb & Whishaw, 2014)

Immediately after a force to the head occurs, there is a ripple effect that happens within the brain (Bailes & Hudson, 2001; Giza & Hovda, 2001). First is a disruption of neuronal membranes, which causes a release of neurotransmitters in the brain. This results in a rapid change of ionic states. Potassium channels open, flooding the extracellular matrix with potassium. The cell then starts to depolarize because of the extracellular matrix flooding. Typically, the glial cells would compensate and take up the excessive extracellular potassium to restore the cells to normal function. However, after brain trauma, the glial cells are sometimes unable to help. Thus, the extracellular potassium continues to increase, causing an even greater neural depolarization of the cells until it reaches a point of neural suppression or spreading depression. In post-concussive trauma, the potassium fluxes diffuse in areas of the brain simultaneously. This spreading is what may account for early loss of consciousness, amnesia, or other cognitive dysfunction right after an injury (Bailes & Hudson, 2001; Kolb & Whishaw, 2014).

In order to quickly restore these ions back to resting state, or normal, the sodium-potassium pumps have to work overtime and need increasing amounts of adenosine triphosphate (ATP) to aid in the process. The acquisition of more ATP triggers a large increase in glucose metabolism (hyperglycolysis). Accelerated use of glucose metabolism leads to an increase in lactate production by the cells resulting in excessive lactate accumulation by the cells. Elevated lactate levels can result in many types of neural dysfunction including acidosis, membrane damage, altered blood brain barrier permeability, and cerebral edema. This in turn causes a diminished cerebral blood flow triggering a "cellular crisis" because there is a mismatch in energy supply and demand. Typically, the post-concussive deficits occur with minimal detectable anatomical pathology with symptoms often resolving over time, suggesting that only temporary neuronal dysfunction occurs rather than cell death (Giza & Hovda, 2001). Giza and Hovda (2001) also suggest that it is the temporary neural dysfunction, however, that leads to acute changes in behavior, such as decreased balance or working memory. Thus, neuromotor and neurocognitive behavior assessments are commonly given after a suspected concussion to provide a window into the underlying pathophysiology after head trauma.

While concussions are typically associated with sort-term neuromotor or neurocognitive dysfunction, long-term dysfunction is also reported (Ingriselli et al., 2014). There are two general types of behavioral effects that result from concussions: 1) impairment of the specific functions associated with the direct impact to that area of the brain (coup) or opposite side of the brain (countercoup) or 2) more generalized impairments due to widespread trauma from the injury. Severe and repeated concussions can lead to worse conditions, including a slower recovery and prolonged impairment in acute and chronic neuromotor and neurocognitive dysfunctions. Generally, the risk of repeated concussion is greatest in the first 7-10 days after return to play (Noble & Hesdorffer, 2013), in part due to the heightened sensitivity to perturbations following the initial head trauma, which increases athletes' vulnerability to post-concussion syndrome (PCS) (Blennow et al., 2012; Kemp, Patricios, & Raftery, 2016). This leads to issues making appropriate return-to-play guidelines in the sport setting, as there can be tension between coaches, athletes, and medical professionals to make sure athletes return as quickly as possible, but also have completely recovered and are no longer in danger of a repeated concussion.

Concussion Assessment Tools

Historically, concussions have challenged sports medicine clinicians and researchers due to the subjective symptoms and vague knowledge that could be obtained in order to make appropriate assessment and treatment decisions. From a diagnostic perspective, one of the perplexing issues with traumatic brain injury is misdiagnosis because chronic effects of the sustained injury are not characterized by obvious neurological signs or abnormalities when looking at a brain in a CT or MRI scan. Magnetic Resonance Spectroscopy (MRS) is the only medical instrument as of now that has the potential to accurately diagnose a TBI (Kolb & Whishaw, 2014). Acute impairment is often associated with injury to the frontal and temporal lobes, where the brain is most susceptible to TBI and concussions (Kolb & Whishaw, 2014). Therefore, a wide variety of tools and assessments have been created to objectively measure behavior in hopes of increasing the diagnostic accuracy after head trauma.

Recent research has aimed to create a more standardized screening to reduce the amount of uncertainty when assessing a potential concussion. One method of detecting a change in neurocognitive and neuromotor function following a suspected concussion is to assess the athlete on the sideline and then compare scores to a previous baseline score, typically taken before the season starts. Two popular assessments are the Sideline Concussion Assessment Tool (SCAT) and Immediate Post-Concussion Assessment and Cognitive Testing (ImPACT). Both include neurocognitive and neuromotor assessments in an effort to quantify behavior associated with head trauma. One advantage to using one of these assessment tools is that they can also act as a preseason evaluation, potentially screening out athletes who have existing head trauma if appropriate normative data are available for comparison.

Having access to preseason evaluations for each athlete prior to the start of a season is recommended to make concussion assessment easier and safer (Wojtys, Hovda, Landry, Boland, & Lovell, 1999). There is a wide disparity between individual athletes in regards to their performance on memory, attention, concentration, motor speed, and control. Preseason testing offers a baseline standard, unique to each athlete, giving a coach or medical professional an idea of each athlete's "normal", or how they functionally preform before a concussion occurs. Those scores can then be compared to when the athlete is assessed following a suspected concussion, allowing the medical staff to accurately see the disparity between non-concussed behavior and concussed behavior to be able to make appropriate decisions for return-to-play (McCrea, Kelly, Randolph, Kluge, & Bartolic, 1998). Individual preseason performance has the greatest clinical accuracy for interpreting post-injury results. However, individual baseline assessment does come with its own assumptions.

Post-concussive return-to-play decisions are dependent on an athlete's baseline performance for comparison purposes. However, baseline testing is vulnerable to athlete manipulation by intentionally performing poorly on a baseline concussion test, which is referred to as "sandbagging"—significantly lowering their baseline scores in order to avoid being benched if a concussion does occur. Sandbagging acts as a threshold buffer, dropping the minimal score an athlete needs to obtain to return-to-play under safe measures, thus decreasing the difference between typical performance and possible neuromotor and neurocognitive deficits following a concussion. There are natural declines in neuromotor and neurocognitive testing scores following a concussion, so the lower score an athlete can establish as their baseline or "normal", the greater the possibility of returning to play before full healing has occurred. Much attention has focused on assuring the integrity of baseline tests by establishing "red flags" as indicators for poor performance, typically two standard deviations below a normative mean, which alerts testers of poor performance (Erdal, 2012). However, Erdal (2012) eludes that athletes seem to still be able to sandbag without detection. Erdal (2012) intentionally looked at the motivations and strategy behind successfully sandbagging without reported "red flags". It was found that 8 athletes out of a group of 75 undergraduate athletes were able to purposefully sandbag their baseline testing by reporting using less purposeful faking strategies, which would typically facilitate errors. This suggests that athletes need significant motivation, instruction, and expertise with specific testing in order to effectively sandbag (Erdal, 2012), which can be the case if the same baseline tests are given season after season

In order to steer away from problems of sandbagging and time commitment of individual baseline testing, another option to detect neurocognitive or neuromotor deficits is to use a normative database made up of scores from numerous athletes participating in the same sport. Although recent research has concluded that both baseline comparisons and normative database comparisons methods have a similar reliability rate in identifying sport related concussions (Schmidt, Register-Mahlik, Mihalik, Kerr, & Guskiewicz, 2012), majority opinion continues to advocate for individual baseline comparison for specificity and increased accuracy (Schmidt et al., 2012; Zimmer, Marcinak, Hibyan, & Webber, 2014).

Concussions: An Important Topic in Sport

Sport-related concussions (SRC) have become a hot topic in the media, news, and research as a major public health concern over the years. As the seriousness of a concussion is better understood, a head injury is being treated differently than an injury to another part of the body. This is due to better tracking of concussion incidence, and the short- and long-term effects of head trauma being better quantified via more sensitive neurocognitive, neuromotor, and neuroimaging assessments. An estimated 1.6 to 3.8 million SRCs are reported each year in the United States in athlete populations (Daneshvar, Nowinski, & Cantu, 2011). A further breakdown by the National Collegiate

Athletic Association (NCAA) reported that college athletes suffered an average of 10,500 concussions within the past five years with approximately 3,400 of them happening in men's American Football. An annual national estimate breakdown by sport between the 2009-2010 and 2013-2014 academic years is as followed (concussion rates per 1,000 athletic exposures):

- Women's Soccer: 6.3
- Men's Football: 6.7
- Women's Ice Hockey: 7.5
- Men's Ice Hockey: 7.9
- Wrestling: 10.9

This has sparked numerous conversations within the NCAA administration to change schools' concussion management plans. In May 2014, the NCAA and U.S Department of Defense (DoD) launched a concussion initiative to enhance the safety of student athletes. More than 16,000 students are currently enrolled with more than 37,000 student-athletes estimated to participate by the end of the three year study.

As the seriousness and importance of concussion research grows, a parallel conversation is also growing. Although the research is limited, data suggests that females experience concussions differently than males (Arnold, 2013; Covassin, Elbin, Crutcher, & Burkhart, 2013; Dick, 2009; Noble & Hesdorffer, 2013). Thus, sex-specific analyses and potentially assessment norms may be warranted relative to concussion assessment and management.

Sex Differences in Concussion

Men's and women's sports are generally separated when referring to sport performance statistics. However, this trend does not typically continue into the concussion space. Most concussion studies focus on males or a combined male/ female population without recognition of sex differences between males and females. With Title IX as part of the Equality in Education Act of 1972, there has been a significant increase in women's participation in sport over the past few decades. The NCAA has reported an 80% increase in female sport participation between 1988 and 2004, while men's sports only increased 20% during that time period. With the increase in sport participation comes an expected increase in sport-related concussions (Covassin et al., 2013).

Numerous epidemiological studies have been conducted in order to understand how women are specifically affected by a concussion. In the collegiate athlete stetting, approximately 11.4% of women athletes will experience a concussion comparative to 7% in men (Noble & Hesdorffer, 2013). A higher percentage may be due to multiple confounding biological differences that separate males and females. Females have differing hormonal, neuroanatomical, and cerebrovascular characteristics such as higher blood flow and increased levels of glucose metabolism, exacerbating the negative effects following a concussion compared to male counterparts (Covassin et al., 2013). General trends show that females tend to have a larger head-to-ball ratio compared to males, specifically in soccer, making females more susceptible to faster acceleration and displacement after heading the ball (Arnold, 2013). A systematic study by Dick (2009) aids in understanding the seriousness of sex differences, finding sex as an independent predictor of brain injury. That is, evidence showed that females experience worse traumatic brain injury outcome compared to males (Dick, 2009). Females have a 1.28 times higher mortality rate compared to males following a moderate severe traumatic brain injury and females are 1.57 times more likely than their male counterparts to experience poorer outcomes after a concussion, including severe disability. Dick (2009) also highlighted a greater cognitive impairment, specifically in simple and complex reaction times, in female athletes compared to males following a concussion. Lastly, females have been suggested to be more likely to report more concussion symptoms, and higher severity of those symptoms resulting in more accurate concussion symptom reporting compared to their male counterparts (Arnold, 2013; Covassin & Elbin, 2011). In a recent article published by Covassin et al. (2016), females reported a longer time off from sport to recover than male counter parts. Specifically, in soccer, female soccer players took an average of 9 days to return compared to 6 days in male populations. The same trend is also seen in basketball with women taking an average of 7 days to return to play while males took only an average of 5 days to recover (Covassin, Moran, & Elbin, 2016). This may be explained by differences seen in symptom reporting. If women are reporting both a higher number of symptoms and more severe symptoms, it could equate to a longer recovery time meaning more time is needed before returning to play to ensure complete recovery. Males report a less total number of symptoms and severity of symptoms leading to less recovery time before returning to play. Therefore, the argument could be made that males and females need to be assessed by sex-specific return-to-play guidelines taking into account both differing symptomology and recovery time patterns.

Tracey Covassin, a leading researcher in this area, has published numerous studies looking at these sex differences specifically in symptomology that was previously mentioned, concussion rates, and neuropsychological function among a college athlete population following a concussion. Some of her and her colleague's main findings include differences between male and female visual memory composite sores and symptoms post-concussion. Concussed female athletes perform significantly worse than concussed male athletes on visual memory tasks (Covassin, Schatz, & Swanik, 2007). If males and females have different scores after a concussion, then an important question arises if sex differences exist between males and females in baseline scores before a concussion occurs. If males and females start in different places in terms of baseline scores, then one can assume that enduring a concussion only exacerbates those differences. However, there is very little research available to address this question.

With this newly emerging trend in literature proposing that males and females experience concussions differently, return-to-play protocol and concussion rehabilitation may also need to differ between male and female athletes. Also, since female athletes are underrepresented in the concussion literature and they have a different profile relative to concussions, this thesis will only focus on female athletes.

The Nature of Sport

The American Academy of Pediatrics published an analysis in 1994 concerning sport participation. In this statement, there was a re-categorization of sport by their probability for collision and contact. Collision sports (e.g., football, ice hockey, rugby) are defined by athlete's purposeful intention of hitting or colliding with one another or an inanimate objects including the ground, with great force during play. In contrast, contact sport athletes (e.g., soccer, baseball, soccer) routinely make contact with each other and objects during play, but with usually less force and intentionality than collision sport athletes. The last category is limited contact sports (e.g., softball, golf) where contact with other athletes or an object is infrequent or inadvertent. For the purpose of this thesis, sport categories will follow the definitions laid out by the American Academy of Pediatrics. This type of categorization is important when examining impact expectation and concussion exposure in sport. The NCAA has developed a concussion management plan in regards to different sport categories stating that impact is largely dependent on contact and exposure (NCAA, 2014). Therefore, the higher the likelihood for impact means a greater risk for a concussion.

The occurrence of concussion is measured as the number of concussions per number of games in one season or specified amount of time, whereas athletic exposure rates account for both practice and game times (Noble & Hesdorffer, 2013). Typically, however, concussion reporting can get messy because often times concussion reporting represents a mixture of first ever concussion and recurrent concussions where one athlete may represent both categories (i.e., a first ever concussion leading to a recurrent concussion within the same reporting period or multiple recurrent concussions). Therefore, most publishers refer to the measurement as occurrence of concussion to eliminate as much crossover as possible.

In collegiate sport populations, concussions represent 5.8% of all collegiate sport injuries and within that percentage, collegiate football represents more than half (55%) of those concussion occurrences (Zuckerman et al., 2015). When taking into account practice time as well, the NCAA reports athletic exposure (1 athletic exposure = participation in 1 game or 1 practice) concussion rates as static over the past decade, with an estimated 2.5 concussions per 1000 athletic competition exposures and 0.4 concussion per 1000 practice exposures (NCAA, 2013; Zuckerman et al., 2015). Although rate of concussion typically depends on player position, in general, football continues to have the overall highest rate of concussion in sport (NCAA, 2013; Zuckerman et al., 2015).

Zuckerman et al. (2015) recently published an article addressing the epidemiology of sports-related concussion in NCAA athletics between the 2009-2010 and 2013-2014 academic years. A total of 1670 SRCs were reported, with 888 out of 1670 happening during competition (53.3%) and 782 (36.8%) in practice. The concussion rates for competition were reported higher than practice rates: 12.84 per 10,000 athletic exposures to 2.57 per 10,000 athletic exposures, respectively. Within all sports, football, categorized as a collision sport, contributed to the greatest number of reported 603 SRCs, 36.1% of the total 1670 concussion reported. This was followed by another collision sport, men's ice hockey, with 13.4% of the total 1670 concussion reported. The third highest was women's soccer, a contact sport, at 8.1% of the 1760 concussions reported. Overall, rates per 10,000 athlete-exposure were different between female sports and male sports. Males had an overall rate of 3.23 while females had a higher overall rate of 3.94. These summaries are congruent with literature patterns suggesting that long-term participation in sport exposes athletes to repetitive, concussive, and sub-concussive head trauma that has great potential to compromise neurocognitive and neuromotor performance (Gavett, Stern, & McKee, 2011; Powell, 2001). Also, higher concussion rates in females versus males compliments earlier findings that females may experience more concussions than males (Dick, 2009; Noble & Hesdorffer, 2013).

Regardless of sex differences and probability of head trauma from sport type, the same family of tests can be used for concussion assessment and management. However, the interpretation of such tests may be sex- or sport-specific. Neuromotor performance is commonly assessed during preseason screening and after a potentially concussive event is balance, as it provides a behavioral measure of sensory integration, the latter of which could be effected after head trauma. The next section outlines how postural control (a form of neuromotor assessment) is used to measure balance.

Balance and Postural Control

Postural control is an umbrella term encompassing the act of maintaining, achieving, or restoring a state of balance during any posture or activity (Pallock et al., 2000). Maintaining balance is critical for successful sport performance and injury prevention. Balance is defined as maintaining the body's center of mass (COM) vertically over the base of support (BOS), relying on continuous feedback from visual, vestibular and somatosensory structures to execute appropriate and coordinated actions (Hrysomallis, 2011).

In order to maintain balance, the COM must stay within the BOS. As the COM moves toward the boundary of the BOS, the feet push on the ground in the opposite direction, causing the COM to move in the counter direction. The location of the average pressure that the feet are applying to the ground is called the center of pressure (COP). Thus, the COP is constantly corralling the COM to stay within the BOS, analogous to a sheep dog (the COP) keeping the sheep (the COM) within the fence (the BOS). Thus, a person's balance ability reflects their ability to control their posture. Since the COM is always moving during upright stance (termed postural sway), researchers commonly examine characteristics of postural sway as a window into neuromotor control. This is due to the fact that maintaining upright stance (a motor task) requires the integration of the visual, vestibular, and somatosensory systems within the central nervous systems (hence the term neuromotor control).

A threat to balance is detected by the afferent or sensory system and a response follows through efferent or motor system (Pallock et al., 2000). Impairments in postural control may increase the risk of injury by altering the proactive and reactive adjustments needed to maintain balance within a sport skill. In many cases following a concussive blow, communication between the visual, vestibular, and somatosensory systems is degraded, resulting in postural instability. Postural control dysfunction is one of the cardinal symptoms following a concussion, typically resolved within 3-5 days post-injury (Buckley, Oldham, & Caccese, 2016). However, if an athlete returns to sport before complete recovery, it could put them at a higher risk for another concussion. Although baseline assessments of balance are recommended prior to the season, these data are commonly used for comparison of post-concussion balance behavior. We are unaware of any research examining baseline postural control prospectively relative to concussion risk. In any case, balance assessments have been recognized as an integral component of evaluation after a concussion with various mechanisms of assessing in both the general sport and clinical settings (McCrory et al., 2012; U.S. Department of Veterans Affairs / Department of Defense, 2016) . The next section focuses on how balance has been measured in both clinical and research settings.

Balance Assessments

Balance assessments in the context of SRCs fall into one of two categories: subjective assessment or objective assessment. Subjective assessment relies on the clinical practitioner to determine a person's balance ability typically based on watching them in a series of posture or walking tasks. This method requires a set of guidelines that the practitioner must follow in order to determine a person's balance ability. Subjective assessments are valuable in the clinic or on the sideline because they typically require little or no equipment and they are relatively quick. However, they do rely on the practitioner's ability to judge a person's balance in line with the guidelines for that test and for all practitioners to assess balance in the same way. This can lead to inconsistencies within and between practitioners. On the other hand, objective assessment is typically conducted with a machine (e.g., forceplate or smartphone), so the reliability between test assessments is reduced. The following paragraphs outline how balance has been assessed both subjectively and objectively.

One of the most common subjective methods of balance assessment in the sports medicine field is the Balance Error Scoring System (BESS) test. The BESS test was designed as a cost effective way to assess athletes balance ability, developed by researchers at the University of North Carolina at Chapel Hill (Guskiewicz, 2011; Riemann, Guskiewicz, & Shields, 1999). The BESS uses three stances (single leg, double leg, and tandem leg) on two differing surfaces (hard and foam surfaces), leading to 6 conditions. Participants are instructed throughout each stance to place their hands on the top of their iliac crests and when their eyes close, the 20 seconds of that particular trial begins (Guskiewicz, Ross, & Marshall, 2001; Riemann et al., 1999). If the participant moves from their starting position with any of the following movements, an error is counted: (1) removing hands from the hips, (2) opening the eyes, (3) taking a step, (4) abduction/flexion of the hip beyond 30 degrees, (5) lifting the heel or forefoot off the ground, or (6) remaining out of the beginning position for more than 5 seconds. After all stances have been completed, errors are added up, giving the clinician a total error score and subjective measurement of balance capabilities. In administering the BESS test one day after a reported concussion, there is an average of 4 errors on a firm surface and 13 errors on a foam surface in a concussed athlete while a control group averages only 2 errors on a firm surface and 6 errors on a foam surface. By day five, a concussed athlete averages 3 errors on a firm surface and 8 errors on a foam surface. As an athlete's neurological system returns to normal in days following a concussive blow, the hope is that the average errors in each stance will decrease demonstrating balance patterns that match baseline scores indicating positive recovery (Riemann & Guskiewicz, 2000). However, the BESS does have mixed reviews with low reliability due to between tester subjectivity in how errors are counted (Chang, Levy, Seay, & Goble, 2014; Hunt, 2009). Also, after multiple administrations, a practice effect was identified (Chang et al., 2014; Hunt, 2009). Therefore, objective methods of balance assessment may provide more sensitivity and specificity to identify balance changes after a concussion over subjective methods that could have between- and within-rater reliability issues.

Objective assessment removes balance assessment subjectivity by using a machine to measure a person's postural sway. This is done by tracking the COP over time, which can provide insight into postural control mechanisms, along with helping to identify when postural control may be compromised after a neurological insult (i.e., head trauma). Postural sway is a distinct, continuous pattern of deviations created by the COP to keep the COM within the BOS. Increased postural sway relative to a baseline test or normative data is associated with postural instability (Chang et al., 2014), which can occur after head trauma. Forceplates are commonly been used to measure COP movement with a high resolution, but have traditionally been confined to the laboratory due to their high cost and need to be in controlled environments (e.g., level surface with low vibration). However, recent technological advances have allowed for the development of portable forceplates that are not limited to the previously identified constraints (Chang et al., 2014).This opens up an avenue for balance testing in a wider variety of settings and could increase the ecological validity of balance assessment. These portable devices are able to measure COP displacement in the anterior/posterior (AP) and medial/lateral (ML) directions independently. While there may be value in examining postural control separately in the AP and ML directions, the metrics used in this thesis will combine the AP and ML time series since there is no current hypothesis suggesting that balance control should be separated in the AP and ML directions in the context of concussion management.

Once the COP profile is measured with a force plate, the characteristics within the COP profile are quantified to objectively assess balance ability. While there are many metrics that have been used to assess postural control, studies have examined which metrics are the most reliable (Lin, Nussbaum, & Madigan, 2008; Ruhe, Fejer, & Walker, 2010; Scoppa, Capra, Gallamini, & Shiffer, 2013) which guided the selection of three COP metrics for this thesis.

The first metric is path length, which quantifies the total distance traveled by the COP in the combined AP and ML directions. Path length is calculated by summing the magnitude of the distance change of the COP at every time step with the following equation:

$$\text{Path Length} = \sum_{i=1}^{N-1} \sqrt{(AP_{i+1} - AP_i)^2 + (ML_{i+1} - ML_i)^2}$$

where N is the number of data points in the COP displacement time series and i is each successive data point (Goble, Manyak, Ahdenour, Raub, & Baweja, 2016).

The second and third metrics quantify the variability of the COP velocity profile in the resultant direction. Variability in human movement is typically considered a reflection of errors in motor control, leading to the assumption that more variability reflects greater neuromotor dysfunction. However, research examining human movement variability over the past 20 years has challenged that assumption (Hausdorff, 2007; Chrisopher Rhea & Kiefer, 2014; Stergiou & Decker, 2011; Vaillancourt, & Newell, 2002) Specifically, variability has been separated in the magnitude of variability (i.e., how much there is) and the structure of variability (i.e., what it looks like). Both have value in evaluating postural control, with the latter potentially providing more sensitivity to small changes not picked up by the former.

The second metric used in this thesis is the magnitude of the COP velocity profile, specifically using the standard deviation. Geurts et al. (1996) found a difference in standard deviation of mean velocity within the static balance test derived from a forceplate. The group with diagnosed TBIs reported higher standard deviations in both the anterior/posterior direction and medial/lateral direction compared to the control group (Geurts, Ribbers, Knoop, & van Limbeek, 1996).

The third metric quantifies the structure of variability using Sample Entropy (SampEn), which is a nonlinear variable often used in balance analyses. This metric provides a measure of how complex a system is by searching for repetition of specific patterns within a time series. A greater number of repeated patterns within a time series indicate a more regular movement pattern and less complexity in the neuromotor system. This equates to more rigid and controlled movements with less fluidity and adaptability. SampEn is computationally similar to approximate entropy (ApEn), which has been used to examine postural control after a concussion. Cavanaugh et al. (2005) examined ApEn to determine whether it could detect changes in postural control after a concussion among athletes without signs of postural instability. Results showed that ApEn was valuable in picking up postural control deficits that were not detected with other metrics.

Postural Control After Sub-Concussive Head Trauma

The previous sections outlined how neuromotor control changes after a clinically diagnosed concussion. However, nearly all head trauma in sports does not lead to a concussion, which has been called sub-concussive head trauma. There has been a recent push in the scientific community to examine not only concussive head trauma, but also sub-concussive head trauma (Rhea et al., 2017; Talavage et al., 2014). It has been suggested that acute and chronic head trauma is analogous to glass, in which there are two ways to break it. You can hit it really hard once (i.e., a concussive hit) or you can repeatedly hit it softly and eventually it will break (i.e., sub-concussive hits). Thus, sub-concussive head trauma may snowball over time, leading to neuromotor or neurocognitive damage and could be equal to or worse than a concussive hit. Sub-concussive hits may produce biochemical changes, potentially leading to neurological problems if enough compound on each other (Johnson, Neuberger, Gay, Hallett, & Slobounov, 2014).

Grysland et al. (2012) looked at the relationship between sub-concussive impacts and measures of neurologic function in collegiate football players and found that neurocognitive and neuromotor (i.e., balance) scores decreased from preseason to post-season with no reported concussions. Johnson et al. (2014) looked at the effects of sub-concussive hits to the head on the brain's neural network during resting-state using functional magnetic resonance. Twenty-four rugby players were screened 24 hours prior to a full contact game to determine a baseline, and then follow-up scanning occurred within 24 hours post game to assess the acute affects. Results showed increased connectivity in some regions of the brain while decreased connectivity in other areas of the brain. Further analyzing was done to assess how a prior history of concussion changed resulting neural network patterns. Players with a prior concussion history exhibited a decrease in connectivity following exposure to sub-concussive head trauma, while those with no history showed increases in connectivity. Lastly, a recent study was published by Abbas et al. (2015), complementing Johnson et al. (2014), looking at neural connection differences in high school football players versus a control group. Resting-state functional magnetic resonance imaging was used to detect brain network patterns before and after a season, with subsequent screenings to track changes across the season. Overall, football athletes portrayed different functional connectivity than the control group for most of the year. A neurological change seems to have accumulated over the year of playing football for the athletes, along with hyper-connectivity, indicating that despite the absence of symptoms typically associated with a concussion, repetitive smaller hits to the head could induce long-term brain damage compared to healthy populations (Abbas et al., 2015). These studies support the notion that sub-concussive hits may be just as dangerous as a concussive hit.

This section described how postural control can be altered, even without a concussion history and in respects to the findings of Johnson et al. (2014), concussion history may be a bigger predictor of negative neural damage following sub-concussive hits to the head. Therefore, it is reasonable to hypothesize that athletes participating in collision sports—activities that have a higher probability of head trauma—would have altered postural control at baseline relative to athletes participating in other types of sports. To test this hypothesis, my advisor and I reached out to Dr. Daniel Goble at San Diego State University. Dr. Goble is part of a team that developed a portable forceplate designed for concussion management. The Balance Tracking System (BTrackS; San Diego, CA) consists of a portable forceplate and software designed to objectively test postural control in a laboratory or field-based setting. The testing consists of three 20 second static stance trials with the eyes closed and feet shoulder width apart. The software records the average path length of the COP during the three trials and archives it for comparison in case a suspected concussion were to occur in the future. The software also has the capability of connecting to Dr. Goble's database (with the users permission), allowing Dr. Goble's team to develop a large database of normative postural control from a wide variety of teams.

For pilot work leading up to this thesis, Dr. Goble gave us access to 10,522 participants who were tested before their season between June 2014 and September 2016. Since my thesis focused on female athletes who participate in collision, contact, or limited contact sports, I filtered the data accordingly and ended up with N=1637 athletes fitting those criteria. The data below show the average path length of the COP by sport type. While the data for female collision sport athletes are limited (N=32), a higher path length value is observed in this population, supporting the hypothesis that sub-concussive trauma may influence baseline postural control.

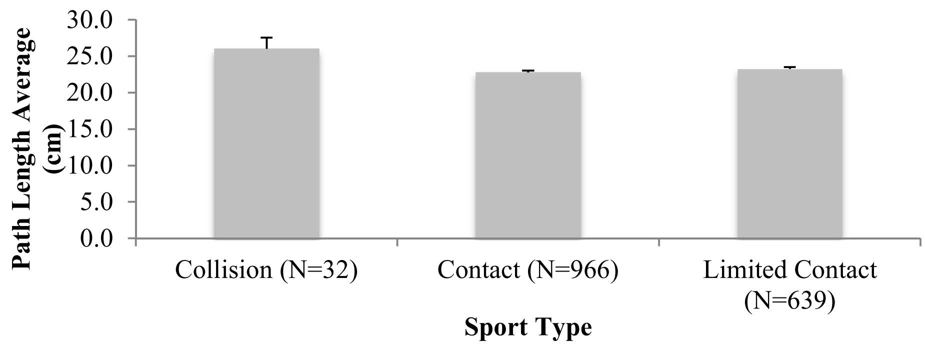

Figure 1. BTracks Scores for 1637 Female Athletes in Different Sport Types

Postural Control in Relation to Sport

Not only does concussive or sub-concussive head trauma influence postural control, but so can expertise. Roerdink and colleagues presented a framework showing how postural control be effected after high skill level has been developed (Roerdink, Hlavackova, & Vuillerme, 2011). Different sports place different demands on the visual, vestibular, and somatosensory systems, affecting balance maintenance between different athletes. Therefore, sport-specific training may lead to the development of different postural control strategies that may show up in preseason baseline testing. Therefore, literature suggests that postural control may fit within the context of sport specificity (Kiers et al., 2013; Lamoth et al., 2009, 2009; Macnamara, Moreau, & Hambrick, 2016).

Literature also suggests that there also may be a direct relationship between deliberate practice and postural control. The operational definition of deliberate practice is stated as engaging in activities specifically to improve performance in a specific domain. Overall, deliberate practice accounts for roughly 18% of variance in sport performance across a single sport (Macnamara et al., 2016). The acquisition of expertise results from adaptations to typical task constraints resulting in cognitive changes, physiological changes, and perceptual-motor skill adaptations to facilitate superior performance (Gruber, Jansen, Marienhagen, & Altenmueller, 2010). Evidence has been shown in laboratory analyses that cognitive adaptions of experts exist within domain-specific constraints and that physiological adaptations happen on a daily basis in response to habitual usage because of the body's natural physiological and neural plasticity (Gruber et al., 2010). Thus the more deliberate practice an athlete experiences within a specific sport, the more likely physiological adaptations have occurred specific to that habitual sport played giving an athlete postural control patterns unique to movement patterns of that particular sport. Chow, Fong, Chung, Ma, and Macfarlane (2015) conducted a sport-specific postural control strategy study among amateur rugby players. They explored the differences in balance strategy and performance between 45 amateur rugby players and 41 healthy active individuals. Performance was measured using the sensory organization test (SOT) and found an independent association between years of rugby training and SOT condition 6 equilibrium score suggesting a relationship between deliberate practice and postural control. A systematic review by Kiers et al. (2013) looked at the relationship between physical activities in sport and postural sway in upright stance and found that in general, sport performers showed less postural sway than controls, and also complimented Hrysomallis' (2011) findings that high-level or elite athletes also showed less postural sway than low-level athletes (Kiers et al., 2013) Overall, findings suggest balance abilities are specific to particular task demands. Hrysomallis (2011) presented a cross-sectional study on the relationship between balance ability and athletic performance at different levels of competition and found a superior balance of elite athletes compared to less experienced counterparts. This may be a result of repetitive experience that influences the neuromotor processes.

Postural Control in Relation to Aging

A final factor that can effect postural control in the context of this thesis is aging. The majority of concussion and sub-concussion research has focused on college students, followed by high school students. This confines the age range of most head trauma studies in the context of sports to ages 16-23. It is well documented that millions of post-college aged adults participate in recreation or semi-professional sports. Female participation in particular is growing, especially in collision sports such as football, rugby, roller derby, and ice hockey. However, there is very little data on recreational and semiprofessional athletes older than 23, especially in the female population. Since aging is well known to alter postural control, it must be accounted for when examining the postural control of recreational and semiprofessional athletes outside of the typically college age.

There is a vast array of literature written about postural control changes with aging. In elderly populations, postural control studies typically examine postural adjustments to perturbations, smooth transition reflecting the natural environment, or in the scope of exercise. Changes in postural control, especially those of maladaptation, may contribute to the increase in number of falls in older adults (Freitas & Durante, 2012). Aging leads to naturally less robust physiological systems overtime, which can decrease the ability to adapt to perturbations. As previously mentioned, balance relies heavily on the integration of visual, vestibular, and somatosensory inputs make appropriate balance adjustments, all of which degrade after young adulthood.

Literature examining postural control in older adults shows a larger degree of variability in COP movements when compared to younger subjects, leading to the conclusion that older adults' balance is less stable (R. van Emmerik, 2002). For example, Amiridis, Hatzitaki and Arabatzi (2003) had participants stand barefoot on a forceplate during a quiet one-legged stance while COP variability was recorded. Results showed that older adults (n=19; age=70) displayed greater CoP excursions compared to the younger population (n=20; age=20). To determine whether practice can reduce the effect of aging, Lamoth and van Heuvelen (2010) examined whether patterns of postural sway of elderly who have deliberately practiced a sport of high specificity (ice speed-skating) are more similar to that of younger subjects than inactive elderly population. Trunk patterns of all subjects were measured with a tri-axial accelerometer with quantified AP and ML acceleration time series, similar to a forceplate. Results showed postural control differences existed between the deliberately practiced elderly group and sedentary elderly group. Also, postural control of the speed skaters was most similar to that of the younger group, suggesting that participating in deliberate practice of specific movements may counteract age related changes in postural control.

As exemplified in the studies above, there is a wide array of literature available on older adult populations pertaining to the degree of specific changes in the nervous system affecting postural control. Yet, the majority of postural control studies in the context of concussion management are on young adults (typically high school athletes or college students). Even though it is clearly evident that, as people age, the nervous system changes leading to different postural control strategies, there is a gap in literature acknowledging this aging difference in the sport context. Athletes older than college students are typically not studied, yet local recreational leagues offering adult league options see large numbers in attendance and participation, making them a large, understudied population.

Current Gaps in the Literature with Regards to This Thesis

Despite the growing body of literature surrounding concussion and efforts by NCAA and other athletic organizations to heighten the awareness of concussions, numerous gaps in the literature still exist. One fundamental observation is that despite the increasing database of published literature, very little work has focused on female athletes. When female have been studies, they are usually combined with mens data, negating any sex difference that may have existed. Thus, females are underrepresented in the concussion literature and present differently after head trauma, which is why this thesis focused on female athletes.

Further, athletes participating in different sport types are commonly combined, disregarding that head trauma probability (concussive or sub-concussive) may influence concussion assessments. Thus, there is a need to separate sports by their determined sporty type, as my pilot data suggests.

Moreover, very little research has focused on sport-specific athlete comparisons, which may provide a window into how sport skills and deliberate practice may influence postural control. This may be another necessary factor that needs to be accounted for when examining postural control across a variety of sports.

Lastly, athletes participating in recreation and semi-professional leagues are typically older than the commonly studied athletes in concussion literature, which could also affect postural control. Collectively, this thesis helped address those gaps by testing female recreational and semi-professional athletes who participated in various sports to determine the extent to which baseline postural control is affected by sport type and specific sport.

CHAPTER III

OUTLINE OF PROCEDURES

Participants

A total of eighty seven healthy recreational and semi-professional athletes were recruited to participate prior to their season starting. Inclusion criteria included normal or corrected to normal vision, no cognitive or physical impairment, no current musculoskeletal injuries, no pregnancies, and an age between 22-40 years old. All participants were from recreational or semi-professional leagues in the Greensboro area. Athletes participating football, roller derby, basketball, and running were recruited.

Instrumentation

COP displacement data were collected at 25 Hz using the Balance Tracking System (BTrackS ™). This forceplate has been validated against research grade forceplates (Chang et al., 2014) and has been recently shown to have better specificity compared to the BESS (Goble et al., 2016).

Procedure

After signing the informed consent form, participants were asked to complete a sport activity questionnaire. Next, participants were asked to stand on the forceplate with their hands on their hips, eyes closed, and feet shoulder width apart. Verbal instruction for every participant were given from a provided script of instructions through the BTrackS software to keep consistency between participants.

Data Collection and Analysis

The Sports Balance software from BTrackS was used to record the COP displacement time series for each trial. The software automatically calculated the average path length from the three trials. To calculate the other dependent variables of interest, the following procedures were used:

1. The COP displacement files were removed from the data collection computer's hard drive and placed into a common folder to be analyzed.
2. The AP and ML time series for each trial were converted into a resultant time series using the following equation:

$$R_d(i) = \sqrt{(AP_{i+1} - AP_i)^2 + (ML_{i+1} - ML_i)^2}$$

   where R_d = the resultant displacement time series, *i* = the data point in the time series, AP = the anterior-posterior displacement time series, and ML = the medial-lateral displacement time series.
3. Each resultant displacement time series were then converted to a resultant velocity time series using the following equation:

$$R_v(i) = \frac{\left(R_{d_{i+1}} - R_{d_i}\right)}{Sampling\ frequency}$$

where R_v = the resultant velocity time series, *i* = the data point in the time series, R_d = the resultant displacement time series, and sampling frequency = 25 Hz (.04 seconds).

4. The mean and standard deviation for the R_v time series in each of the three trials were calculated and averaged.
5. Next, the R_v time series were analyzed using SampEn with an *m* of 3 and *r* of (0.3 × SD) for each of the three trials and averaged.
6. The three dependent variables of interest (path length, velocity standard deviation, velocity SampEn) were added to a master SPSS (IBM, Armonk, NY) file.

To address the hypothesis, a one-way ANOVA for each of the three dependent variables was used to determine if athletes in each sport exhibit different postural control. Alpha was set at 0.05. If differences were found between sports, characteristics derived from the sport history questionnaire was to be used to examine factors that associate to those differences, such as concussion history, number of years in a sport, and perceived skill level.

CHAPTER IV

MANUSCRIPT

Introduction

Maintaining upright posture is a vital component of many activities of daily living, as well as being critical for successful sport performance. In order to maintain upright stance, a person's center of mass (COM) must stay within their base of support (BOS) requiring the visual, vestibular, and somatosensory systems to work together to provide feedforward and feedback information to the body. However, this sensory information can be disrupted and/or less salient after head trauma, leading to the cardinal symptom of postural control challenges after a concussion (Buckley, Oldham, & Caccese, 2016). Following an initial concussion, athletes are at a higher risk of sustaining an injury or another concussion because the proactive and reactive adjustments needed to maintain balance during play are compromised (Kolb & Whishaw, 2014; Oliaro, Anderson, & Hooker, 2001; Pallock et al., 2000). Therefore, balance assessments have been recognized as an integral component of concussion evaluation in both sport and clinical settings to help with concussion management (McCrory et al., 2012; U.S. Department of Veterans Affairs / Department of Defense, 2016).

Historically, concussions have been a perplexing physiological phenomenon due to the subjective symptoms and vague knowledge obtained to make appropriate assessment and treatment decisions. One method to aid clinicians in determining whether a concussion may have occcured is to measure the change in neurological function between a baseline measurement and measurement after head trauma. Having access to 20 evaluations for each althete prior to a season is recommended to better understand how an athlete ‘normally’ functions before head trauma (Schmidt Register-Mahlik, Mihalik, Kerr, & Guskiewicz, 2012; Wojtys, Hovda, Landry, Boland, & Lovell, 1999; Zimmer, Marcinak, Hibyan, & Webber, 2014). Baseline scores act as a comparisson tool between non-concussed behavior and concussed behavior to assist in making more objective clinical decisions and return-to-play rediness, with balance assessment serving as an integral component of neuromotor testing (McCrea et al., 1998, McCrory et al., 2013).

Balance assessments in the sport space typically falls into two categories: subjective assessment or objective assesment. Subjective assessment relies on the practicioner or athletic trainer to quantify postural control ability based upon a followed set of guidelines, such as the Balance Error Scoring System (BESS) (Guskiewicz, 2011; Riemann, Guskiewicz, & Shields, 1999). Objective assessments remove balance assessment subjectivity by using technology to measure postural sway. Typically, this is done by tracking center of pressure (COP) over time to help identify when postural control is compromised due head trauma. Increased postural sway relative to a baseline score or normative data is associated with postural instability, and with the help of technological advances, can be captured in a wider variety of settings through the use of portable force plates (Chang et al., 2014).

Sport related concussions (SRC) have become a major public health concern over the years as the seriousness of a concussion is better understood. With the help of technology and research, the concussion literature has become more vast. However, as the body of literature grows, there is a gap that also keeps growing—sex disparity in concussion research. Most concussion studies focus on males or a combined male/female population without regards to sex differences between males and females. Literature is starting to suggest that men and women exerience concussions differently with respect to symptom reporting, lingering symptomology, and recovery due to hormonal, neuroanatomical, and cerebrovascular differences between males and females (Arnold, 2013; Covassin et al., 2013; Covassin & Elbin, 2011; Dick, 2009). Moreover, it is not well understood how females participating in diverse sports may differentially experience the effects of head truama. The likelihood of an athlete receiving a concussion varies with head trauma exposure rate and magnitude, which differs between sports (NCAA, 2014). Using the American Academy of Pediatrics 1994 guidelines, sports can be catagorized by the probably of physical contact, leading to four sport categories: (1) collision sports (e.g., football, ice hockey, roller derby), (2) contact sports (e.g., basketball, soccer, baseball), (3) limited contact sports (e.g., softball, volleyball), and (4) non-contact sports (e.g., golf, archery).

Since collison sports have the highest probability of head trauma leading to a concussion, which can have a lingering effect on balance control (Rhea et al., 2017), it is plausible that athletes participating in collision sports may have different balance baselines than athletes particiapting in other sport catagories. This may especially true for female athletes, who have been reported to experience more concussions that lead to more severe and prolonged symptoms relative to males in the same sport (Arnold, 2013; Covassin et al., 2013, 2013; Dick, 2009; Dvorak, McCrory, & Kirkendall, 2007; King, 2014). Therefore, the purpose of this study was to determine the extent to which postural control in female athletes may differ between four distinct sports at baseline. Balance assessments were performed in the preseason in order to get a baseline measurement. It was hypothesized that the poorest postural control would be exhibited in the sports with the most potential for head trauma (football and roller derby).

Methods

Participants

Healthy, community recreational female athletes (*N* = 87, *M* age = 31.2, *SD* age = 6.2) participated in the study during their preseason. Athletes participating in football, roller derby, basketball, and running were recruited from the Greensboro and Raleigh, North Carolina area. Participant demographics are presented in Table 1. All participants had normal or corrected-to-normal vision, no current musculoskeletal injuries, no cognitive impairment, able to stand unaided for one minute, and were not currently pregnant. Each participant provided an informed consent and completed a sport activity questionnaire. All procedures for the study were approved by the University of North Carolina at Greensboro Institutional Review Board.

Instrumentation

Center of pressure was recorded with the Balance Tracking System (BTrackS; San Diego, CA), which consists of a portable force plate and software designed to objectively test postural control in a laboratory or field-based setting. BTrackS collects at a pre-established frequency of 25Hz. Each participant went through standard BTrackS procedures, consisting of four 20-second static stance trials with eyes closed, feet shoulder width apart, and hands on hips. The first trial is considered a familiarization practice trial, so results and calculations are averaged from the remaining three trials.

Experimental Design

Participants signed a consent form and provided sport history information through a questionnaire. Three questions from the sport history questionnaire were rused to measure perceived skill level in their sport and concussion history. For skill level, the participants were asked to self-report what skill level they considered themselves to be at that time and was coded as: beginner = 1, novice = 2, advanced = 3, master = 4, and pro = 5. There were no definitions or examples provided for any of the skill level categories. Two questions were asked regarding concussion history for each participant. The first question asked if the participant had been diagnosed with a concussion and was coded as no = 0 and yes = 1. The second question asked if the participant felt like they may have gotten a concussion, but have never been diagnosed and was coded as no = 0 and yes = 1. Self-reported height and mass were recorded in the BTrackS software. Next, the participant was walked through a pre-determined instructional script offered by the software provider, and then asked to step onto the force plate with feet shoulder width apart, put their hands on their hips, and when ready, close their eyes, after which the 20-second trial would begin. Following the 20 seconds, the athlete was asked to step off the force plate, and then when ready, repeated the procedure three more times for a total of four trials, the first serving as a familiarization trial.

BTrackS measures COP displacement in the anterior/posterior (AP) and medial/lateral (ML) directions independently, which can be used to derive the path length of the COP, a metric commonly that can be used to measure postural control deficits after head trauma (Goble, Manyak, Ahdenour, Raub, & Baweja, 2016). Next, we combined the AP and ML time series into a resultant time series to better characterize multi-dimensional postural control. We then converted the resultant displacement time series into a resultant velocity time series, which has been suggested to reflect the information used by the nervous system to maintain an upright stance (Delignières, Torre, & Bernard, n.d.; Jeka, Kiemel, Creath, Horak, & Peterka, 2004). The variability of the resultant COP velocity profile was then quantified to objectively assess balance ability, as a change in variability is commonly used as an indication of altered postural control. Standard deviation (SD) was used to quantify the magnitude of variability in postural control and sample entropy (SampEn) was used to quantify the structure of variability. SampEn quantifies repeating patterns in a time series, leading to a value typically ranging from 0 to 2. A greater number of repeated patterns is indicative of a more regular movement pattern (SampEn tending toward 0), reflecting more rigid movements with less fluidity and adaptability. Thus, three dependent variables were derived: (1) path length, (2) SD of the resultant COP velocity, and (3) SampEn of the resultant COP velocity.

Data Reduction

The CoP displacement data from BTrackS was exported into individual text files and then imported into MATLAB (MathWorks Inc., Natick, MA). Custom MATLAB scripts were written to analyze the data. Data were first converted into a resultant time series using the following equation:

$$R_d(i) = \sqrt{(AP_{i+1} - AP_i)^2 + (ML_{i+1} - ML_i)^2}$$

where R_d = the resultant displacement time series, i = the data point in the time series, AP = the anterior-posterior displacement time series, and ML = the medial-lateral displacement time series. Path length was calculated by summing the magnitude of the distance changes in resultant COP at every time step. Next, each resultant displacement time series were then converted to a resultant velocity time series using the following equation:

$$R_v(i) = \frac{\left(R_{d_{i+1}} - R_{d_i}\right)}{Sampling\ frequency}$$

where R_v = the resultant velocity time series, i = the data point in the time series, R_d = the resultant displacement time series, and sampling frequency = 25 Hz (.04 seconds). The magnitude of variability was measured by calculating the SD of each R_v time series. Last, the structure of variability was measured by calculating SampEn of each R_v time series. An $m = 3$ and $r = 0.3 \times$ SD of the time series was used for the SampEn analysis based on an optimized technique for identifying m and r values (Lake, Richman, Girffin, &

Moorman, 2002). The selected values are consistent with previous research examining the SampEn of COP velocity (Glass, Ross, Arnold, & Rhea, 2014).

Statistical Approach

Separate one-way ANOVAs were used for the each of the three dependent variables to determine if athletes in each sport exhibit different postural control strategies (α=.05). Separate Bonferroni corrected *t*-tests were used as follow-up analyses when appropriate. Pearson correlations were used to examine the association between perceived skill and concussion history with the dependent variables. All data were then imported and analyzed in SPSS (IBM, Armonk, NY). The three trials were then averaged for each dependent variable.

Results

Demographic, perceived skill, and concussion history data are presented in Table 1.

Table 1. Age, Skill Perception, and Concussion History. Participant sport history by sport for age, perceived skill level, history of concussion and perceived concussion.

Sport	n	Age: M(SD)	Perceived Skill	History of Concussion: M(SD)	Perceived Concussion: M(SD)
Football	45	33.1(6.5)	______	______	______
Roller Derby	15	30.2(5.3)	2.3(.85)	.071(.27)	.43(.51)
Basketball	19	27.0(3.8)	3.3(.83)	.11(.32)	.11(.31)
Running	9	34(10.8)	2.7(.50)	.11(.33)	.22(.44)

There were no differences observed in path length $F(3, 84) = 0.79$, $p = .50$, $\eta_p^2 = .03$) or SD of COP velocity, $F(3, 84) = 0.38$, $p = .80$, $\eta_p^2 = .01$) between sports (Figures 2A and 2B). However, statistically significant differences were observed between sports in SampEn of COP velocity, $F(3, 84) = 6.3$, $p = < .001$, $\eta_p^2 = 0.18$. Bonferroni-corrected follow-up *t*-tests showed that basketball sports had higher SampEn than football, roller derby, and running sports ($p < .001$) (Figure 2C).

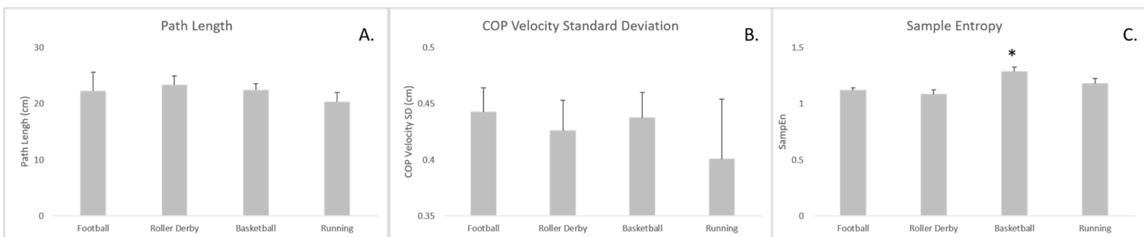

Figure 2. BTrackS Scores for Between Sports. BTrackS results for football, roller derby, basketball, and running athletes for path length (A.), COP velocity standard deviation (B.) and sample entropy (C.).

Table 2 presents further analysis using a bivariate, Pearson's correlation, (2-tailed) looking at the correlation between path length, SD of the resultant COP velocity, SD of the resultant COP velocity, age, perceived skill, diagnosed concussion, and perceived concussion to further explain the lack of significance between sports except in sample entropy. Results show no significant correlation relating to age or perceived skill level. However, concussion history does show significance in relation to COP velocity SD in the basketball sport group ($p < .05$).

Table 2. Dependent Variables Correlated with Age, Skill Perception, and Concussion History. Pearson's 2-tailed correlation of three dependent variables with age, perceived skill, and concussion history. ** significant at $p>.05$

Age		**Path Length**		**SD**		**SampEn**	
		r	**Sig.**	**r**	**Sig.**	**r**	**Sig.**
	Football	.04	.78	.04	.79	.26	.09
	Roller Derby	.14	.63	.34	.24	-.17	.55
	Basketball	.28	.26	.13	.62	-.31	.22
	Running	.01	.98	.04	.92	.16	.68
Perceived Skill							
		r	**Sig.**	**r**	**Sig.**	**r**	**Sig.**
	Football	---------	---------	-------	--------	-------	--------
	Roller Derby	-.18	.54	-.35	.24	-.44	.14
	Basketball	-.21	.39	-.22	.38	-.19	.46
	Running	.37	.33	.40	.28	-.53	.14
Diagnosed Concussion							
		r	**Sig.**	**r**	**Sig.**	**r**	**Sig.**
	Football	---------	---------	-------	--------	-------	--------
	Roller Derby	-.17	.55	-.20	.49	-.20	.49
	Basketball	.40	.10	.67	**.002***	-.25	.30
	Running	-.48	.19	-.40	.29	.37	.32
Perceived Concussion							
		r	**Sig.**	**r**	**Sig.**	**r**	**Sig.**
	Football	---------	---------	-------	--------	-------	--------
	Roller Derby	.17	.55	.15	.61	-.20	.49
	Basketball	.40	.10	.67	**.002***	-.25	.30
	Running	-.48	.19	-.40	.28	.37	.32

Discussion

This study examined baseline postural control in female athletes participating in one of four specific sports (football, roller derby, basketball, and running) to determine if the sport-specific skills influenced baseline postural control. The data indicate that basketball sport athletes had a higher SampEn, but no differences in path length or SD. These data support previous findings that highlight the utility of nonlinear metrics as a more sensitive analysis of postural control relative to linear metrics. However, a combination of both linear and non-linear metric provides a holistic view of the athletes sport performance.

The higher SampEn values in the basketball sport athletes suggests the adoption of a less regular pattern in postural control, typically interpreted as more adaptive balance. Interestingly, the football, roller derby and running sports had statistically similar SampEn, both of which were lower than the basketball sport. A concussion has been shown to lower entropy in a static balance task (Cavanaugh et al., 2006) and repeated sub-concussive head trauma can lead to long-term neurological dysfunction (Abbas et al., 2015; Gavett et al., 2011; Gysland et al., 2012; Laubscher, Dijkstra, Strydom, & Peters, 2006)—observations that may partially account for the lower SampEn in the football and roller derby sport athletes. The lower SampEn values in the running sport athletes are a bit less straight forward. Since these athletes don't typically receive head trauma during their sport, it is possible that their sport requires less adaptive balance in the context of sport-specific skills, leading to more regular patterns in their postural control.

The finding that linear metrics (path length and SD) didn't exhibit differences between sports, but SampEn did supports previous findings that nonlinear metrics are more sensitive to small, yet potentially important changes in balance behavior (Cavanaugh, Guskiewicz, Giuliani, et al., 2005; Cavanaugh, Guskiewicz, & Stergiou, 2005). Linear metrics provide a summary of the behavior over a set time, whereas nonlinear metric describe the structure of the time-evolution of the behavior. This leads to a more fine-tuned analysis of the behavior, allowing for the potential of picking up on differences in behavior that may be masked by linear metrics—an observation that has been repeated made in posture and gait research (Cavanaugh, Guskiewicz, & Stergiou, 2005; Hausdorff, 2007; Stergiou & Decker, 2011; van Emmerik, 2002; van Emmerik, Ducharne, Amado, & Hamill, 2016). However, a combination of both linear and non-linear metrics provides a holistic view of the athlete sport performance.

There was also a statistically significant, positive correlation in the basketball COP velocity SD with concussion history ($r=.67$, $p>.05$). Standard deviation metric defines the amount of variability in the behavior with a higher standard deviation away from the mean (path length) generally meaning more variability in the system (Rhea & Keifer, 2011). Given the positive association to concussion history, one plausible cause of variability could be due to a higher overall total number of concussions or severity of concussion impact with lingering deficits (refer to table 2). However, as previously mentioned, a history of concussions will typically lower sample entropy metrics suggesting a more rigid postural control pattern, yet the basketball group had a statistically significant higher sampEn suggesting more adaptability which may be complimented by the increase in SD variability. Without a full concussion history, it is difficult to speculate if the concussions could be isolated to basketball and how long ago they were sustained.

Since our project focused on female athletes, it makes a unique contribution to the literature by showing that linear metrics can mask changes in behavior in this population. Previous work has focused on males or a combined male/female population.

Postural control strategies may be fairly similar between athletes when doing a static balance task, however different results may be observed during a. It is also important to note that athletes in this study were participants in community recreation leagues, which differs from the athletic population typically studied in concussion-related research (e.g., high school, college, and professional athletes). Thus, there may be more variance in the postural control abilities between players in the same sport due to a wider range of athletic ability and practice time, which could also partially account for the lack of difference between sports.

Some limitations to this study are as follows. First, the sample size for each sport group was small, and not equal across neither sports nor sport types. Secondly, the environments in which the participants were asked to complete the balance assessment were as controlled as possible, but had noise from music and non-participant conversations that could have influenced their balance performance. Lastly, the window of ‘preseason’ expanded to include three weeks into the playing season for the basketball cohort, exposing athletes to a higher chance for head contact and exposure compared to other athletes who were truly at preseason. Similarly, there is no traditionally defined preseason for running sports, so true baseline measures are harder to capture compared to seasoned sports.

Future directions for this research should focus on increasing sample size to determine if similar findings occur given larger numbers in the various sports. Similarly, adding a variety of sports within the sport categories may not only help to see distinctions within the sport type itself, but also may help to better understand postural control strategies among different sports. Lastly, expanding to include a younger age range and tracking them across their season would help explore how age and development influence postural control.

In conclusion, maintaining postural control is a crucial component of daily life, especially for athletic success. Our data indicate that postural control strategies between sport categories may be different, with the basketball sport athletes adopting a more adaptive balance strategy when compared to football, roller derby, and running sport athletes. Also, sport-specific skills may not have as much influence in a static, baseline postural control task. Nevertheless, this study sets up the foundation for future research in female concussion work, specifically in relation to postural control.

CHAPTER V

DISCUSSION

The motivation behind this study was to determine the extent to which different sports may lead to different baseline postural control assessment in female athletes. Currently, the majority of concussion research literature is centered on young male adults between the ages of 18-22 years old. However, as concussion research expands, the role of sex and age needs further attention to more closely match the demographics of the wider sport participation population. This study served to better understand a largely unrepresented population in concussion research (female athletes), highlight the use of portable force plate technology as a valuable and tangible objective measurement in concussion assessment, and to continue filling in the gaps of the extent to which sport participation may influence baseline postural control measures.

Athletes that participated in basketball, a contact sport, showed greater complexity in postural control when compared to football, roller derby and running sport athletes, indicating that their sport experience with respect to head trauma and/or skill development leads to different balance ability. There were no significant differences observed in path length or SD between sports, showing that nonlinear metrics may be more sensitive to changes in behavior. Further, the lack of path length differences between sport types in this project corroborate the findings from our recent analysis showing that male and female athletes ages 18-24 have no path length differences in static balance task between sport types (although a sex difference was observed) (Schleich, Duffy, Ross, Goble, & Rhea, under review). Collectively, the data are beginning to suggest that sex may be a more important factor than sport type with respect to baseline postural control.

Overall, this study specifically contributes to the literature by showing that there are may be performance differences between sport athletes in relation to postural control at baseline for female athletes. Also, although this study has a relatively small sample size, it demonstrates differences in postural control between athletes participating in different sports may be observed if a sensitive metric (such as SampEn) is used. These data set the stage for a stronger understanding of how previous experiences may influence baseline postural control, which may have implications for injury risk going into the season. Large scale prospective studies are needed to examine that postulate more thoroughly, in conjunction with a full battery of clinical assessments of neurological functioning. Nevertheless, these data help address the issue of females being underrepresented in the concussion literature.

REFERENCES

Abbas, S., Poole, T., Breedlove, E., Leverenz, E., & Nauman, E. (2015). Alteration of default mode network in high school football athletes due to repetitive subconcussive mild traumatic brain injury: A resting-state functional magnetic resonance imaging study. Brain Connectivity. *Brain Connectivity*, *5*(2), 91–101.

American Academy of Pediatrics. (2001). Medical Conditions Affecting Sport Participation. Pediatrics.

Arnold, C. (2013). Concussion in women. *Lancelot Neurology*, *13*, 136–137.

Bailes, J., & Hudson, V. (2001). Classification of sport-related head trauma: A spectrum of mild to severe injury. *Journal of Athletic Training*, *36*(3), 236–243.

Blennow, K., Hardy, J., & Zetterberg, H. (2012). The Neuropathology and Neurobiology of Traumatic Brain Injury. *Neuron*, *76*(5), 886–899.

Bressel, E., Yonker, J., Kras, J., & Heath, E. (2007). Comparison of static and dynamic balance in female collegiate soccer, basketball, and gymnastics athletes. *Journal of Athletic Training*, *42*(1), 42.

Buckley, T., Oldham, J., & Caccese, J. (2016). Postural control deficits identify lingering post-concussion neurological deficits. *Journal of Sport and Health Science*, *5*, 61.

Cavanaugh, J. ., Guskiewicz, K. M., Giuliani, C., Marshall, S., Mercer, V. S., & Stergiou, N. (2005). Detecting altered postural control after cerebral concussion in athletes with normal postural stability. *British Journal of Sports Medicine*, *39*(11), 805–811.

Cavanaugh, J. ., Guskiewicz, K. M., Giuliani, C., Marshall, S., Mercer, V. S., & Stergiou, N. (2006). Recovery of postural control after cerebral concussion: new insights using approximate entropy.

Cavanaugh, J. ., Guskiewicz, K. M., & Stergiou, N. (2005). A Nonlinear Dynamic Approach for Evaluating Postural Control. *N. Sports Med*, *35*(11), 935.

Center for Disease Control. (2015). What Is a Concussion? Center for Disease Control.

Chang, J., Levy, S., Seay, S., & Goble, D. (2014). An alternative to the balance error scoring system: using a low-cost balance board to improve the validity/reliability of sports-related concussion balance testing. *Clinical Journal of Sport Medicine*, *24*(3), 256–262.

Rhea, C.K, Kuznetsov, N. A., Robins, R. ., Jakiela, J. ., Lojacono, C. ., Ross, S. E., … Wright, W. . (2017). Dynamic balance decrements last longer than 10 days following a concussion. Presented at the International Society of Posture & Gait Research, international conference, Ft. Lauderdale, FL.

Covassin, T., & Elbin, R. . (2011). The female athlete: the role of gender in the assessment and management of sport-related concussion. *Clinics in Sports Medicine*, *30*(1), 125–131.

Covassin, T., Elbin, R. ., Crutcher, B., & Burkhart, S. (2013). The management of sport-related concussion: considerations for male and female athletes. *Translational Stroke Research*, *4*, 420–424.

Covassin, T., Moran, R., & Elbin, R. . (2016). Sex Differences in Reported Concussion Injury Rates and Time Loss From Participation: An Update of the National Collegiate Athletic Association Injury Surveillance Program From 2004–2005 Through 2008-2009. *Journal of Athletic Training*, *51*(3), 189–194.

Covassin, T., Schatz, P., & Swanik, C. B. (2007). Sex Differences in Neurophychological Funciton and Post-Concussion Symptoms of Concussed Collegiate Athletes. *Neurosurgery*, *61*, 345–351.

Daneshvar, D., Nowinski, C., & Cantu, R. (2011). The Epidemiology of Sport-Related Concussion. *Clinics in Sports Medicine*, *30*(1), 1–17.

Dick, R. . (2009). Is there a gender difference in concussion incidence and outcomes? *British Journal of Sports Medicine*, *43*(Supp 1), i46–i50.

Dvorak, J., McCrory, P., & Kirkendall, D. . (2007). Head injuries in the female football player: incidence, mechanisms, risk factors and management. *British Journal of Sports Medicine*, *41*, i44–i46.

Erdal, K. (2012). Neuropsychological Testing for Sports-related Concussion: How Athletes Can Sandbag their Baseline Testing Without Detection. *Archives of Clinical Neurophychology*, *27*, 473–479.

Freitas, S. ., & Durante, M. (2012). Joint coordination in young and older adults during quiet stance: effect of visual feedback of the center of pressure. *Gait & Posture*, *35*(1), 83–87.

Gavett, B., Stern, R., & McKee, A. (2011). Chronic Traumatic Encephalopathy: A Potential Late Effect of Sport-Related Concussive and Subconcussive Head Trauma. *Clinics in Sports Medicine*, *30*(1), 179–xi.

Geurts, A. C., Ribbers, G., Knoop, J., & van Limbeek, J. (1996). Identification of Static and Dynamic Postural Instability Following Traumatic Brain Injury. *Arch Phys Med Rehabilitation*, *77*, 639–644.

Glass, S. M., Ross, S. E., Arnold, B. L., & Rhea, C. K. (2014). Center of pressure regularity with and without stochastic resonance stimulation in stable and unstable ankles. *Athletic Training and Sports Health Care*, *6*(4), 170-178.

Giza, C., & Hovda, D. (2001). The neurometabolic cascade of concussion. *Journal of Athletic Training*, *36*(3), 228–235.

Goble, D., Manyak, K., Ahdenour, T., Raub, M., & Baweja, H. (2016). An initial evaluation of the BTrackS balance plate and sports balance software for concussion diagnosis. *International Journal of Sports Physical Therapy*, *11*(2), 149.

Gruber, H., Jansen, P., Marienhagen, J., & Altenmueller, E. (2010). Adaptations during the acquisition of expertise. *Talent Development and Excellence*, *2*(1), 3–15.

Guskiewicz, K. (2011). Balance assessment in the management of sport-related concussion. *Clinics in Sports Medicine*, *30*(1), 89–102.

Guskiewicz, K., Ross, S., & Marshall, S. (2001). Postural Stability and Neuropsychological Deficits After Concussion in Collegiate Athletes. *Journal of Athletic Training*, *36*(3), 263–273.

Gysland, S., Mahalik, J., Register-Mahlik, J., Trulock, S., Shields, E., & Guskiewicz, K. (2012). The relationship between subconcussive impacts and concussion history on clinical measures of neurologic function in collegiate football players. *Annals of Biomedical Engineering.*, *40*(1), 14–22.

Hausdorff, M. (2007). Gait dynamics, fractals and falls: Finding meaning in the stride-to-stride fluctuations of human walking. *Human Movement Science*, *26*, 555–589.

Hrysomallis, C. (2011). Balance ability and athletic performance. *Sports Medicine*, *41*(3), 221–232.

Hunt, T. (2009). The reliability of the modified Balance Error Scoring System. *Clinical Journal of Sport Medicine: Official Journal of the Canadian Academy of Sport Medicine*, *19*(6), 471–5.

Ingriselli, J., Register-Mahlik, J., Schmidt, J., Mahalik, J., Goerger, B., & Guskiewicz, K. (2014). Outcomes, utility, and feasibility of single task and dual task intervention programs: Preliminary implications for post-concussion rehabilitation. *Journal of Science and Medicine in Sport*, *17*, 580–585.

Johnson, B., Neuberger, T., Gay, M., Hallett, M., & Slobounov, S. (2014). Effects of Subconcussive Head Trauma on the Default Mode Network of the Brain. *Journal of Neurotrauma*, *31*, 1907–1913.

Kemp, S., Patricios, J., & Raftery, M. (2016). Is the content and duration of the graduated return to play protocol after concussion demanding enough? A challenge for Berlin 2016. *British Journal of Sports Medicine*, *50*(11), 644–645.

Kiers, H., van Dieen, J., Wittink, H., & Vanhees, L. (2013). A systematic review of the relationship between physical activities in sports or daily life and postural sway in upright stance. *Sports Medicine*, *43*(11), 1171–1189.

King, N. S. (2014). A systematic review of age and gender factors in prolonged post-concussion symptoms after mild head injury. *Brain Injury*, *28*, 1639–1645.

Kolb, B., & Whishaw, I. Q. (2014). *An Introduction to Brain and Behavior* (4th ed.). NY: Worth Publishers.

Lake, D. E., Richman, J. S., Griffin, M. P., & Moorman, J.R. (2002). Sample entropy analysis of neonatal heart rate variability. *Am J Physiol Regul Integr Comp Physiol, 283*(3), R789-R797.

Lamoth, C., van Lummel, R., & Beek, P. (2009). Athletic skill level is reflected in body sway: A test case for accelometry in combination with stochastic dynamics. *Gait & Posture*, *29*(4), 546–551.

Laubscher, J., Dijkstra, H., Strydom, G., & Peters, E. (2006). Incidence of mild and very mild traumatic brain injuries in a secondary school rugby team: health promotion, fitness and wellness. *Afr J Phys Health Educ Recreat Dance*, *12*(4), 468–482.

Lin, D., Nussbaum, M., & Madigan, M. (2008). Reliability of COP-based postural sway measures and age-related differences. *Reliability of COP-Based Postural Sway Measures and Age-Related Differences*, *28*(2), 337–342.

Macnamara, B., Moreau, D., & Hambrick, D. (2016). The Relationship Between Deliberate Practice and Performance in Sports: A Meta-Analysis. *Perspectives on Psychological Science*, *11*(3), 333–350.

McCrea, M., Kelly, J., Randolph, C., Kluge, J., & Bartolic, E. (1998). Standardized Assessment of Concussion (SAC): On-Site Mental Status Evaluation of the Athlete. *Journal of Head Trauma Rehabilitation*, *13*(2), 27–35.

McCrory, P., Meeuwisse, W., Aubry, M., Cantu, B., Dvorak, J., Echemendia, R., & Sills, A. (2013). Consensus statement on concussion in sport: the 4th International Conference on Concussion in Sport held in Zurich, November 2012. *British Journal of Sports Medicine*, *47*(5), 250–258.

NCAA. (2013, December 18). SSI task force explores issues, challenges around concussions [Text]. Retrieved October 8, 2016, from http://www.ncaa.org/health-and-safety/medical-conditions/ssi-task-force-explores-issues-challenges-around-concussions

NCAA. (2014). Guideline 21: Sport-Related Concussion. 2014-2015 NCAA Sports Medicine Handbook.

Nelson, L., Janecek, J., & McCrea, M. (2013). Acute Clinical Recovery from Sport-Related Concussion. *Neuropsychology Review*, *23*, 285–299.

Noble, J., & Hesdorffer, D. (2013). Sport-related concussions: a review of epidemiology, challenges in diagnosis, and potential risk factors. *Neuropsychology Review*, *23*(4), 273–284.

Oliaro, S., Anderson, S., & Hooker, D. (2001). Management of Cerebral Concussion in Sports: The Athletic Trainer's Perspective. *Journal of Athletic Training*, *36*(3), 257–262.

Paillard, T., & Zemkova, E. (2014). Sport-Specific Balance Develops Specific Postural Skills/Author's Reply to Paillard T:''Sport-Specific Balance Develops Specific Postural Skills''. *Sports Medicine*, *44*(7), 1019.

Pallock, A., Durward, B., Rowe, P., & Paul, J. (2000). What is balance? *Clinical Rehabilitation*, *14*(4), 402–406.

Powell, J. (2001). Cerebral Concussion: Causes, Effects, and Risks in Sports. *Journal of Athletic Training*, *36*(3), 307–311.

Rhea, C., & Kiefer, A. (2014). Patterned variability in gait behavior: How can it be measured and what does it mean? In *Gait Biometrics: Basic Patterns, Role of Neurological Disorders and Effects of Physical Activity*. Hauppauge, NY: Nova Science Publishers.

Rhea, C., Kiefer, A., Wright, G., Raisbeck, L., & Haran, F. J. (2015). Interpretation of postural control may change due to data processing techniques. *Gait & Posture*, *41*(2), 731–735.

Rhea, C., Kuznetsov, N. A., M, J., Yangi, M. ., Long, B., Haran, F. J., … Duckworth, J. . (in press). Development of a portable tool for screening neuromotor sequelae from repetitive low-level blast exposure. *Journal of Military Medicine*.

Riemann, B., & Guskiewicz, K. (2000). Effects of Mild Head Injury on Postural Stability as Measured Through Clinical Balance Testing. *Journal of Athletic Training*, *35*(1), 19–25.

Riemann, B., Guskiewicz, K., & Shields, E. (1999). Relationship between clinical and forceplate measures of postural stability. *Journal of Rehabilitation*, *8*, 71–82.

Roerdink, M., Hlavackova, P., & Vuillerme, N. (2011). Center-of-pressure regularity as a marker for attentional investment in postural control: a comparison between sitting and standing postures. *Human Movement Science*, *30*(2), 203–212.

Ruhe, A., Fejer, R., & Walker, B. (2010). The test–retest reliability of centre of pressure measures in bipedal static task conditions – A systematic review of the literature. *Gait & Posture*, *32*, 436–445.

Schleich, K.N., Duffy, D.M., Ross, S.E., Goble, D., & Rhea, C.K. Pre-season postural control as a function of sport type, age, and sex. *North American Society for the Psychology of Sport and Physical Activity*, San Diego, CA, June 2017, national conference, under review.

Schmidt, J. ., Register-Mahlik, J., Mihalik, J. P., Kerr, Z. ., & Guskiewicz, K. (2012). Identifying impairments after concussion: Normative data versus individualized baseline. *Medicine & Science in Sports & Exercise*, *44*, 1621–1628.

Scoppa, F., Capra, R., Gallamini, M., & Shiffer, R. (2013). Clinical stabilometry standardization: basic definitions–acquisition interval–sampling frequency. *Gait & Posture*, *37*(2), 290–292.

Stergiou, N., & Decker, L. (2011). Human movement variability, nonlinear dynamics, and pathology: Is there a connection? *Human Movement Science*, *30*, 869–888.

Talavage, T. ., Nauman, E., Breedlove, E., Yoruk, U., Dye, A. ., Morigaki, K. ., & Leverenz, E. (2014). Functionally-detected cognitive impairment in high school football players without clinically-diagnosed concussion. *Journal of Neurotrauma*, *31*(4), 327–338.

U.S. Department of Veterans Affairs / Department of Defense. (2016). VA/DoD clinical practice guideline for the management of concussion-mild traumatic brain injury. Veterans Health Administration, The Management of Concussion-mild Traumatic Brain Injury Working Grou.

Vaillancourt, D. ., & Newell, K. . (2002). Changing complexity in human behavior and physiology through aging and disease. Neurobiology of Aging. *Neurobiology of Aging*, *23*(1), 1–11.

van Emmerik, R. (2002). On the Functional Aspects of Variability in Postural Control. *Exercise and Sport Sciences Reviews*, *30*(4), 177–83.

van Emmerik, R. ., Ducharne, S. ., Amado, A. C., & Hammil, J. (2016). Comparing dynamical systems concepts and techniques for biomechanical analysis. *Journal of Sport and Health Science, 5*(1), 3–13.

Wojtys, E., Hovda, D., Landry, G., Boland, A., & Lovell, M. (1999). Concussion in sports. *American Orthopaedic Society for Sports Medicine*, *27*(5), 676–687.

Zemkova, E. (2014). Sport-specific balance. *Sports Medicine*, *44*(5), 579–590.

Zimmer, A., Marcinak, J., Hibyan, S., & Webber, F. (2014). Normative Values of Major SCAT2 and SCAT3 Components for a College Athlete Population. *Applied Neuropsychology: Adult*, *22*(2), 132–140.

Zuckerman, S., Kerr, Z., Yengo-Kahn, A., Wasserman, E., & Covassin, T. (2015). Epidemiology of Sports-Related Concussion in NCAA Athletes From 2009-2010 to 2013-2014. *American Journal of Sports Medicine*, *43*(11), 2654.

APPENDIX A

UNIVERSITY OF NORTH CAROLINA AT GREENSBORO

CONSENT TO ACT AS A HUMAN PARTICIPANT: LONG FORM

Project Title: Postural control differences among collision, contact, and non-contact sport athletes.

Principal Investigator: Kristen Schleich
Faculty Advisor: Christopher K. Rhea, Ph.D.

Participant's Name: ____

What are some general things you should know about research studies?
You are being asked to take part in a research study. Your participation in the study is voluntary. You may choose not to join, or you may withdraw your consent to be in the study, for any reason, without penalty.

Research studies are designed to obtain new knowledge. This new information may help people in the future. There may not be any direct benefit to you for being in the research study. There also may be risks to being in research studies. If you choose not to be in the study or leave the study before it is done, it will not affect your relationship with the researcher or the University of North Carolina at Greensboro. Details about this study are discussed in this consent form. It is important that you understand this information so that you can make an informed choice about being in this research study.

You will be given a copy of this consent form. If you have any questions about this study at any time, you should ask the researchers named in this consent form. Their contact information is below.

What this study is about?
This is a research project. The goal of this study is to examine postural control among different sport athletes to determine if different postural control patterns exist.

Why are you asking me?
You are being asked to participate because you are an athlete who currently participates in a collision sport, contact sport or non-contact sport. You must be able to stand for at least one minute and have normal or corrected to normal vision. You should not participate should you have any other musculoskeletal injuries, pain/discomfort when standing, cognitive impairment, or pregnancy. You must be at least 18 years of age to participate

What will you ask me to do if I agree to be in the study?
You will be asked to partake in the following events:
1. You will be asked to stand for 20s with your feet shoulder width apart, hands on your hips and eyes closed on a force plate.
2. You will be asked to step off and rest for 30 seconds.
3. You will be asked to repeat this series of events three more times for a total of 1 minute 20 seconds with a 30 second rest between each 20s stance.

At the end of the session, I will send you an email with an attached questionnaire. This questionnaire should take roughly 20 minutes to complete, and will ask questions about your sport performance history.

The approximate participation time is 5 minutes. You may stop the study at any time, for any reason.

Is there any audio/video recording?
There will be no video or audio recording during the testing session.

What are the dangers to me?
The Institutional Review Board at the University of North Carolina at Greensboro has determined that participation in this study poses minimal risk to participants.

If you have questions, want more information or have suggestions, please contact Kristen Schleich, knschlei@uncg.edu or Christopher Rhea at ckrhea@uncg.edu. If you have any concerns about your rights, how you are being treated, concerns or complaints about this project or benefits or risks associated with being in this study please contact the Office of Research Integrity at UNCG toll-free at (855)-251-2351.

Are there any benefits to me for taking part in this research study?
There are no direct benefits to you for participating in this study.

Are there any benefits to society as a result of me taking part in this research?
The results of this project may inform basic and clinical science about postural differences between athletes that particpiate in a variety of sport. The findings from this study will help increase knowledge specifically within the concussion field, in respect to how postural control may be specific to sport and if a concussion does occur, how an athlete should recover following return-to-play guidelines.
Will I get paid for being in the study? Will it cost me anything?
There are no compensations for participating in this study. There are no costs to you for participating in this study.

How will you keep my information confidential?
All information that is obtained from this study is strictly confidential unless disclosure is required by law. All data (written and electronic) will only contain your assigned code number. The list connecting your name to your assigned code number will be kept in a locked file cabinet within a locked office in the VEAR laboratory separate from all data. The VEAR laboratory is

protected by an intellikey. All consent forms will be maintained in a confidential file only accessible by the investigator and faculty advisor. When the study is completed and the data have been analyzed, this list will be destroyed. Your name will not be used in any report. The consent forms will be kept in a file in a locked room for three years at which time they will be destroyed by shredding. All data will be stored on the principal investigator's personal computer identified only by subject number. All data disks will be erased once all manuscripts of the data have been submitted and published for two years. A photocopy of this original consent form will be provided to you for your records.

What if I want to leave the study?
You have the right to refuse to participate or to withdraw at any time without penalty. If you choose to withdraw, it will not affect you in any way, and you may request that any of your data which has been collected be destroyed (unless it is in a de-identifiable state). The investigators also have the right to stop your participation at any time. This could be because you have had an unexpected reaction, or have failed to follow instructions, or because the entire study has been stopped.

What about new information/changes in the study?
If significant new information relating to the study becomes available which may relate to your willingness to continue to participate, this information will be provided to you.

Voluntary Consent by Participant:
By signing this consent form you are agreeing that you have read, or it has been read to you, and you fully understand the contents of this document and are openly willing to take part in this study. You are also confirming that all of your questions concerning this study have been answered. By signing this form, you are agreeing that you are 18 years of age or older and are agreeing to participate.

Signature: ____ *Date:* ________________________

APPENDIX B

SPORT ACTIVITY QUESTIONAIRE

Section I: SPORT HISTORY

1. Please identify which sport you are participating in:

2. How old were you when you began playing your particular sport?

3. Have you ever participated in an organized competition of your chosen sport?
   (if you answered no, go to Section II: Sport Training)

4. What level of sport participation would you consider yourself?
   Beginner
   Novice
   Advanced
   Master
   Pro

5. What is the highest level of competition you have participated in for your particular sport?

6. On average, how many times do you compete in your particular sport? (outside of practice times)

7. Have you clinically been diagnosed with a concussion?

8. Do you feel like you may have gotten a concussion, but have never been diagnosed?

Section II: SPORT TRAINING

1. Do you have a personal training coach?

2. Do you follow an annual training plan?

3. How many months per year do you spend training for your sport?

4. On average, how many weeks per year do you take off from training/ playing?

5. Have you previously or are you currently regularly active in another sport(s) as well?

This following section will aid us in gaining information about your past and current training history. Please fill out the questions only if they are relevant to you, if they are not relevant place leave them blank.

We are interested in what you presently would do in a typical practice session.

Activity:	**Time spent in one practice:**
Warm-up, cool down & stretch	
Speed & Power (sprints, intervals etc.)	
Endurance (long distance etc.)	
Technique (drills, kicking, etc.)	
Total typical practice session	
Outside of practice/ games	**Time spent:**
Weights	
Running	
Any other specific regimen	
Total typical training:	

Section III: DELIBERATE PRACTICE

1. How many hours would you say you participate in this current sport per week?

2. How many hours of training is devoted to deliberate practice?
(Deliberate practice refers to any time spent which would not typically be defined as "fun" but working on areas of improvement that do not come naturally such as a free throw shot, corner kick, agility; deliberately working on a skill specifically to practice.)

3. What types of movements or skills do you deliberately practice?