

A Study of Visual and Sensory Performance, Collision Anticipation, and Head Impact
Biomechanics in College Football Players

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ABSTRACT

JACQUELINE A. HARPHAM: A Study of Visual and Sensory Performance, Collision Anticipation, and Head Impact Biomechanics in College Football Players
(Under the direction of Jason P. Mihalik)

The purpose of this study was to determine the relationship between traditional and visual sensory measures of reaction time; and the associations between visual and sensory performance, collision anticipation, and head impact severity in college football players. Thirty-eight collegiate football players participated in the study. We used real-time data collection instrumentation to record head impact biomechanics during games and practices. Our findings reveal no significant correlations between reaction time on traditional and visual sensory measures and no significant association between level of collision anticipation and head impact severity. We found a significant association between head impact severity and level of visual and sensory performance for multiple assessments. Our findings reveal a link between level of visual and sensory performance and head impact biomechanics. Future research will allow clinicians to have the most appropriate testing batteries to identify at-risk athletes and create interventions to decrease their risk of injurious head impacts.

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CHAPTER I

INTRODUCTION

Concussion has been defined as a complex pathophysiologic process affecting the brain, induced by traumatic biomechanical forces that typically result in an impairment of neurologic function and clinical symptoms such as disturbances of vision and equilibrium (McCrory, Meeuwisse et al. 2009). Sport-related concussions have become a major public health concern, with approximately 3.8 million sports-related traumatic brain injuries occurring in the United States each year (Langlois, Rutland-Brown et al. 2006). Concussions can occur in any sport, but it is widely accepted that the majority of sport-related concussions occur in contact or collision sports, such as football. Football is one of the most popular sports among high school and collegiate males, with approximately 1.1 million high school participants and 60,000 collegiate male participants in programs nationwide (Bracken 2007; 2011). Concussions account for a high percentage of overall injuries at both the collegiate and high school level of football. In collegiate athletes, concussions accounted for 6.8% of injuries sustained during fall games, second only to knee internal derangements (Dick, Ferrara et al. 2007). A similar trend is seen at the high school level, with concussions accounting for 8.9% of all total injuries (Gessel, Fields et al. 2007)

Mechanisms of injury for concussions include both direct and indirect head impacts. A direct impact involves an injurious blow making direct contact with the head. An indirect impact occurs when an impact sets the head in motion without directly

coming into contact with it (Guskiewicz and Mihalik 2011). Direct and indirect impacts are caused by a combination of two types of forces: linear and rotational (Bailes and Cantu 2001). As with other injuries, it is believed that the severity of a concussion is related the magnitude, direction, and distribution of the forces applied to the brain (Guskiewicz and Mihalik 2011). Although the exact role of linear and angular accelerations on head impact severity is not entirely clear, it is thought that the ability to dissipate these forces associated with high magnitude impacts would decrease a person's risk of sustaining a concussion.

Researchers have attempted to develop a more sophisticated understanding of the causes and factors that are related to concussion. One area has focused on studying the role of collision anticipation in head impacts. Previous studies have shown head impact severity is lessened in youth ice hockey players when collisions are anticipated (Mihalik, Blackburn et al. 2010); however, this has not been extensively studied in collegiate football players. Another factor that may influence anticipation and affect an individual's ability to withstand head impact forces is their level of visual and sensory performance. The brain receives sensory information from the eyes, integrates that with somatosensory and vestibular input from other sensors, and produces an appropriate motor response. Individuals with higher levels of visual and sensory performance, including the characteristics of visual acuity and contrast sensitivity, are able to respond to their environment in a more efficient and appropriate way (Zimmerman, Lust et al. 2011). Several tools exist to evaluate and train components of an individual's level of visual and sensory performance. Visual training—extent of visual fields, fields of recognition, accuracy of depth perception, and dynamic visual acuity—has been found to be

transferable to the performance of athletes (Stine, Arterburn et al. 1982). In addition to the athlete's performance on the field, it is plausible that an athlete's visual and sensory performance is also related to their ability to anticipate and react to impending head impacts on the field; thus, addressing a new area of research with the goal of preventing injury while concurrently improving athlete performance.

Evaluating visual and sensory performance may be used to identify at-risk athletes, and lead to prospective interventions designed to reduce injury and decrease an athlete's overall risk of sustaining injurious head impacts. Along this same underlying tenet, an evaluation of visual and sensory performance includes an assessment of an athlete's functional reaction time. It is believed that the functional impairments associated with prolonged reaction time could put an athlete at increased risk for an injurious head impact (Eckner, Lipps et al. 2011). Traditionally, we have recorded reaction time using computerized neurocognitive testing using tasks that are far dissimilar to those that are ultimately experienced by athletes in their sports. Identifying relationships between traditional measures of reaction time and visual sensory reaction time as measured by the Nike SPARQ Sensory Station, we will be better positioned to develop more appropriate testing batteries to evaluate an athlete's level of visual and sensory performance to be used for injury prevention interventions. Therefore, the purpose of this study was to 1) determine the relationship between traditional measures of reaction time and reaction time as measured by the Nike SPARQ Sensory Station, 2) determine the association between level of visual and sensory performance and head impact severity in college football players, 3) determine the association between collision anticipation and head impact severity in college football players.

Research Questions

Research Question 1 (Prospective): Is there a significant correlation between reaction time scores on traditional reaction time measures (CNS Vital Signs, ANAM, Clinical Reaction Time Apparatus), and reaction time as measured by the Nike SPARQ Sensory Station?

Research Question 2 (Prospective): Is there a significant association between level of visual and sensory performance (high vs. low) and head impact severity (mild, moderate, or severe) in college football players?

Research Question 3 (Retrospective): Is there a significant association between collision anticipation (anticipated vs. unanticipated) and head impact severity (mild, moderate, or severe) in college football players?

Research Hypotheses

- 1) There will be a significant correlation between scores on traditional measures of reaction time and reaction time as measured by the Nike SPARQ Sensory Station.
- 2) A high level of visual and sensory performance will be associated with less severe head impacts compared to a low level of visual and sensory performance.
- 3) Unanticipated collisions sustained during a college football game will be associated with more severe head impacts compared to anticipated collisions.

Definition of Terms

- 1) Linear Acceleration: a measure of the rate of change in velocity of an object over time along a specific one-dimensional axis, which is reported in meters/sec² or as in terms of gravitational acceleration (g).

- 2) Rotational Acceleration: the rate of change of the angular velocity of an object over time, which is reported in radians/seconds².
- 3) Head Impact Technology Severity Profile (HITsp): a weighted composite score encompassing linear and rotational accelerations, Gadd Severity Index, Head Injury Criterion, and impact location.
- 4) Anticipated collision: the athlete was looking in the direction of the collision at the time of impact and was in a position of athletic readiness.
- 5) Unanticipated collision: the athlete was not looking in the direction of the collision at the time of impact and was not in a position of athletic readiness.
- 6) High Level Visual and Sensory Performer: individuals scoring in or above the 51st percentile within our sample of subjects on the Nike SPARQ Sensory Station evaluation of visual and sensory performance
- 7) Low Level Visual and Sensory Performer: individuals scoring in or below the 49th percentile within our sample of subjects on the Nike SPARQ Sensory Station evaluation of visual and sensory performance

Operational Definitions

Head impact: A head impact will be defined as those head impacts measuring greater than or equal to 10g (Guskiewicz, Mihalik, et al., 2007; McCaffrey, et al., 2007; Mihalik, et al., 2007; Schnebel, et al., 2007).

Severe linear acceleration head impact: A severe head impact will be defined as those head impacts measuring greater than or equal to 106 g in linear acceleration (Zhang, et al., 2004).

Moderate linear acceleration head impact: A moderate head impact will be defined as those head impacts measuring greater than 66 g and less than 106 g in linear acceleration (Zhang, et al., 2004).

Mild linear acceleration head impact: A mild head impact will be defined as those head impacts measuring less than or equal to 66 g in linear acceleration (Zhang, et al., 2004).

Severe rotational acceleration head impact: A severe rotational head impact will be defined as those head impacts measuring greater than or equal to 7900 rad/s² in rotational acceleration (Zhang, et al., 2004).

Moderate rotational acceleration head impact: A moderate head impact will be defined as those head impacts measuring greater than 4600 rad/s² and less than 7900 rad/s² in rotational acceleration (Zhang, et al., 2004).

Mild rotational acceleration head impact: A mild head impact will be defined as those head impacts measuring less than or equal to 4600 rad/s² in rotational acceleration (Zhang, et al., 2004).

Assumptions

- 1) The helmets were fitted properly at the beginning of the season and remained properly fitted throughout the season.
- 2) All athletes put forth maximal effort during the initial testing of visual and sensory performance and reaction time.
- 3) The Nike SPARQ Sensory Station is a valid measure of visual and sensory performance.

- 4) The Head Impact Telemetry System is a reliable measure of head impact biomechanics.

Limitations

- 1) This single football team represents a small sample size that may not represent a larger population of athletes.

Delimitations

- 1) The length of data collection was limited to one football season.
- 2) Only athletes from the University of North Carolina football team were used in this study.
- 3) The Nike SPARQ Sensory Station was the only test of visual and sensory performance used.

Clinical Significance

If there is a relationship between level of visual and sensory performance, collision anticipation, and head impact biomechanics, then visual and sensory performance evaluation and training devices could be used to identify at-risk athletes and create interventions to hopefully decrease their overall risk of injurious head impacts. Further, if we can determine the relationship between traditional measures of reaction time and reaction time as measured by the Nike SPARQ Sensory Station we can develop the most appropriate testing battery to assess an athlete's level of visual and sensory performance that could be used to create a more effective preventative measure.

CHAPTER II

REVIEW OF THE LITERATURE

Definition

Concussion has been defined as a complex pathophysiologic process affecting the brain, induced by traumatic biomechanical forces that typically result in an impairment of neurologic function and clinical symptoms such as disturbances of vision and equilibrium (McCrory, Meeuwisse et al. 2009)

Epidemiology

Traumatic brain injury (TBI) is a serious public health issue in the United States. The Centers for Disease Control and Prevention estimate that 1.4 million traumatic brain injury-related emergency room visits, hospitalizations, and deaths occur each year in the United States. This may even be an underestimate due to the fact that many individuals who sustain TBIs do not seek the appropriate medical care (Langlois, Rutland-Brown et al. 2006). Sports are among the leading cause of mild traumatic brain injury (mTBI) or concussion. An estimated 3.8 million sport-related concussions occur annually in the United States (Langlois, Rutland-Brown et al. 2006). Concussions can occur in any sport, but it is widely accepted that the majority of sport-related concussions occur in contact or collision sports. In a summary of the 16 years of injury surveillance data collected by the National Collegiate Athletic Association (NCAA), concussions represent 5-18% of reported injuries. The leading sports in concussion incidence are women's ice hockey

(18.3%), men's ice hockey (7.9%), women's lacrosse (6.3%), men's football fall season (6.0%), and men's football spring season (5.6%) (Hootman, Dick et al. 2007).

Concussions account for a high percentage of overall injuries at both the collegiate and high school levels of football. At the collegiate level, concussions account for 6.8% of injuries in fall games, 5.5% of injuries in fall practices, and 5.6 % of injuries in spring practices(Dick, Ferrara et al. 2007). At the high school level, concussions account for 5.6-8.9% of injuries (Guskiewicz, Weaver et al. 2000; Gessel, Fields et al. 2007). Guskiewicz et al. found differences in concussion incidence among Division I, II, and III collegiate football programs with the highest incidence rate found in Division III programs (5.5%), followed by Division II (4.5%) and Division I (4.4%) (Guskiewicz, Weaver et al. 2000).The literature supports differences in concussion rates among the different player positions and play types, although there is inconsistency in which positions are at the greatest risk. In one study involving high school athletes, linebackers and running backs accounted for 40.9% and 29.4% of the concussions sustained by defensive and offensive players, respectively. Most concussive injuries occurred during running plays, specifically tackling or being tackled accounted for 67.6% of concussions (Gessel, Fields et al. 2007).

The rate of concussion has increased an average of 7% over the course of the 16 years of NCAA injury surveillance data collection (Hootman, Dick et al. 2007). Along with the steadily increasing rate of concussion, participation in high school and collegiate sports has also increased over the past decade. There are currently 1.1 million high school and 60,000 collegiate male participants in football programs nationally (Bracken

2007; 2011). The increasing injury rates for concussion at the collegiate and high school level make it clear that developing prevention strategies is of the utmost importance.

Pathophysiology

The pathophysiology of brain injury has been divided into two types of trauma: focal and diffuse. Focal trauma is the result of a direct blow, resulting in penetrating or tearing of the cerebral tissue and associated bleeding. These injuries include cortical or subcortical brain contusions, and subdural and epidural hematomas. Concussions are characterized as a diffuse axonal injury, which involves shearing of the white matter fiber tracks throughout the cerebral tissue. Cognitive, memory, and motor deficits post-concussion are associated with the degree of disruption at the axonal level in particular areas of the brain (Bailes and Cantu 2001).

Following biomechanical injury to the brain, a series of neurometabolic events occur that together account for the pathophysiology of concussion. First, there is an abrupt release of neurotransmitters followed by a period of unchecked ionic influx. Binding of excitatory neurotransmitters results in continued neuronal depolarization and a consequential efflux of potassium and influx of calcium. This results in an ionic shift at the cellular level leading to acute and subacute changes in cellular physiology (Giza and Hovda 2001).

Acute changes in cellular physiology include an increased activity of the sodium-potassium pump in an attempt to restore the normal neuronal membrane potential. This increased cellular activity requires adenosine triphosphate (ATP), suddenly increasing the glucose metabolic demand. This period of “hypermetabolism” occurs in a time of

decreased cerebral blood flow following injury. This imbalance leads to an energy crisis due to the inability to supply the glucose needed to maintain membrane potential. It is thought that this could be the cause of the brain's increased vulnerability; the brain is unable to respond to a second injurious mechanism and as a result faces longer lasting deficits (Giza and Hovda 2001). Following the initial jump in glucose metabolism comes a period of depressed glucose utilization. Calcium begins to accumulate and results in impaired mitochondrial oxidative metabolism and neural connectivity due to neurofilament and microtubule disruption. Calcium also activates cellular pathways that eventually lead to cell death (Giza and Hovda 2001).

Sport-Related Concussion: Biomechanics

Just like with all injuries, a sound understanding of the biomechanics of concussion are critical in the development of prevention strategies. Mechanisms of injury for concussions include both direct and indirect head impacts. A direct impact involves an injurious blow making direct contact with the head. An example of this in football is a helmet-to helmet contact. An indirect impact occurs when an impact sets the head in motion without directly hitting it. An example of this in football is during a tackling play in which no actual contact was made with the head, yet the head is still set in motion due to the force of the tackle (Guskiewicz and Mihalik 2011). Direct and indirect impacts are caused by a combination of two types of forces: acceleration-deceleration (linear) and rotational (angular) (Bailes and Cantu 2001). Acceleration-deceleration forces usually result in linear, tensile, and compressive strains on the cerebral tissue as the result of a moving person/head hitting a stationary object or a stationary person/head getting hit by a

moving object. Rotational forces affect the brain because of the brain's attachment at the foramen magnum and spinal cord. Both linear and rotational forces can be present during an injurious mechanism to the brain, however it is believed that usually one force is the main cause (Bailes and Cantu 2001).

Researchers have attempted to develop a more sophisticated understanding of the causes and factors that are related to concussion through empirical and analytical methods of biomechanical analysis. Accelerometers can be inserted into helmets to collect data on head impact acceleration, magnitude, frequency, and location. Empirical methods usually involve linear and angular accelerometry along with video footage collected during sporting events, while analytical methods involve laboratory replication of observed impacts to predict the body's biomechanical response (Guskiewicz and Mihalik 2011).

In 1994, The NFL's Committee on Mild Traumatic Brain Injury initiated a series of studies using analytical biomechanical analysis methods to further the understanding of the biomechanics of concussion. Concussive impacts had a change in head velocity and peak head acceleration greater than that of non-concussive impacts. Concussive impacts were strongly correlated with severity index (SI) and Head injury criterion (HIC) (Pellman, Viano et al. 2003). The majority of the hits were between one player's helmet and another player's helmet, arm, or shoulder pad. Most impacts were high on the helmet (Pellman, Viano, Tucker, & Casson, 2003). The analytical methods used to study head impact biomechanics have limitations. The reconstruction of the impacts is a complex method that involves many steps, leaving many places for error to occur. First, there is a lack of precision from the method observing video footage to determine impact location,

direction, and velocity. Further, the crash test dummies use a head-neck-torso model that is less than the size of an average NFL player. While the error levels for calculating angular accelerations fell within the expected boundaries of a reliable study, a more sound method is needed to fully expand our knowledge of head impact biomechanics if we want to be able to develop appropriate prevention methods (Newman, Beusenbergh et al. 2005).

The second method used to study head impact biomechanics is empirical. Many researchers have begun using a combination of video footage and linear/angular accelerometry to measure head impacts in vivo. This provides a way to capture head impact biomechanical data in real time. Researchers have tried various methods to capture this data, including mounting accelerometers in mouthguards or more commonly into the helmets of collision sport athletes.

There is little research on the mouthguard accelerometry, as this method is more novel with regards to head impact biomechanical analysis. The few studies that use mouthguard accelerometry (Lewis, Naunheim et al. 2001; Higgins, Halstead et al. 2007) have limitations. The current research in this area has only attempted to measure linear acceleration with a single accelerometer. Measurement of rotational acceleration, which is thought to be more closely related to head injury, requires the use of more than one sensor. Additionally, mouthguard accelerometry studies have tended to use laboratory drop tests with a head form model, which may not correlate to on-field measures with actual athletes. By collecting data in pre-determined laboratory type settings, these studies lack the credibility of measuring in vivo impacts. More research needs to be done

with mouthguard accelerometry before it can be accepted as an appropriate way to measure head impact biomechanics.

A much more common empirical method uses in-helmet accelerometry with the use of the Head Impact Telemetry System (HIT System). Researchers can use a combination of video footage and linear/angular accelerometry to measure head impacts in vivo. This provides a way to capture head impact biomechanical data in real time. There are a series of head impact biomechanical measures that have been studied including linear acceleration, rotational acceleration, Head Impact Technology Severity Profiles (HITsp), frequency of head impact, and location of head impact. Researchers have implemented the HIT system to broaden their knowledge of head impact biomechanics and how it relates to various aspects of concussions.

Although the early studies that involving the HIT System had limitations, they were important for recognizing the importance of measuring head impact biomechanics in vivo. One attempt at a sport comparison was made with a multi-sport study that was completed with a very small sample size, including an ice hockey defenseman, a football offensive lineman, a football defensive lineman, and a soccer player. This study is limited by a small sample size and only collecting data on linear acceleration (Naunheim, Standeven et al. 2000). Researchers began to expand on this early work of Naunheim et al. using larger sample sizes. However, because they did not track the same players consistently, they were unable to perform any further statistical analysis regarding player position, play type, etc. Despite the lack of ability for further statistical analysis, these early studies addressed the importance of collecting real-time data for the study of head impact biomechanics, rather than the previously discussed laboratory video

reconstruction analytical methods. (Duma, Manoogian et al. 2005; Brolinson, Manoogian et al. 2006)

The HIT System has been used with aims of identifying differences in head impact biomechanics between different positions and event types in football. Player position and event type differences have been found in frequency and location of the impact (Broglia, Sosnoff et al. 2009; Crisco, Fiore et al. 2010), head linear accelerations (Mihalik, Bell et al. 2007), and head rotational accelerations (Broglia, Sosnoff et al. 2009) of head impacts sustained by football players. While several studies have found that a greater number of head impacts are sustained during games than practices (Crisco, Chu et al. 2004; Broglia, Sosnoff et al. 2009), there are conflicting results on whether higher linear and rotational accelerations occur during impacts sustained practices or games (Mihalik, Bell et al. 2007; Broglia, Sosnoff et al. 2009; Crisco, Fiore et al. 2010). These previous studies have shown that there is likely a relationship between head impact frequency, magnitude, and event type, however more research is needed to determine the exact relationship that exists.

Differences in frequency and magnitude of head impacts between level of play, player positions and play type have been identified. One study implemented the HIT System to compare the head impact biomechanics of collegiate and high school football athletes. Collegiate football players tended experience more frequent impacts with higher magnitude compared to high school players at similar positions (Schnebel, Gwin et al. 2007) At the collegiate level, offensive and defensive linemen sustained the highest number of head impacts in practices and games (Crisco et al., 2010)(Mihalik, Bell et al. 2007). Offensive linemen sustain greater linear accelerations than defensive linemen and

defensive backs and offensive backs and linebackers sustain higher acceleration impacts than defensive linemen and defensive backs. There was a strong association between position and high-magnitude impacts, with offensive backs being more likely to sustain an impact of greater than 80g than defensive linemen, defensive backs, offensive linemen, linebackers, and wide receivers (Mihalik, Bell et al. 2007).

There are also differences in location of impact between position types in football. Most impacts occur to the front of the helmet (Broglia, Sosnoff et al. 2009), followed by the back of the helmet (Crisco et al., 2010)(Mihalik, Bell et al. 2007). Defensive backs, defensive linemen, linebackers, and offensive linemen had more impacts to the front of the helmet than the back; with offensive linemen sustaining the most impacts to the front compared to other positions. Quarterbacks had more impacts to the back of the helmet than to the front (Crisco et al., 2010). Head impacts to the top of the helmet have high accelerations than impacts to other locations on the helmet (Mihalik, Bell et al. 2007; Broglia, Sosnoff et al. 2009). There is a strong association between high-magnitude impact and location of impact, with athletes more likely to sustain an impact of greater than 80g to the top of the helmet (Mihalik, Bell et al. 2007).

The identified positional and event type differences led to the discussion of differences in head impact biomechanics that occur throughout different play types in a football game. There has been an identified interaction between play type and closing distance during special teams plays on the biomechanical measure of HIT_{sp}, with impacts during special teams following long closing distances tending to be the most severe (Ocwieja, Mihalik et al. 2012).

Another area of interest is the relationship between head impact biomechanics and clinical outcome after subconcussive head impacts. College football players sustain approximately 1000 subconcussive hits throughout a single season, however there is little to no impact on clinical measures in concussion tests (Gysland, Mihalik et al. 2011), postural stability, or cognitive scores (McCaffrey, Mihalik et al. 2007) following these subconcussive head impacts. However, a slight increase in symptoms has been associated following high-magnitude impacts sustained by college football players (McCaffrey, Mihalik et al. 2007).

The HIT System has been implemented to relate head impact biomechanics to clinical measures of concussion. This has been studied at both the collegiate (Guskiewicz, Mihalik et al. 2007) and high school (Broglia, Eckner et al. 2011) levels. No relationship was found between head impact biomechanics and injury severity. Additionally, no relationship was found between head impact biomechanics and symptom scores, cognitive function, and postural stability. This particular area of research is difficult and lacks statistical support because of small number of concussions sustained throughout a testing period (Guskiewicz, Mihalik et al. 2007; Broglia, Eckner et al. 2011).

The HIT System has been implemented to attempt to use biomechanical measures to identify a concussion injury threshold. This would be beneficial to allow the system to be used as a sideline tool to help assist clinicians in the classification and identification of concussive impacts. The following biomechanical measures have been identified as having a possible use at identifying injury threshold: rotational acceleration, resultant linear acceleration, impact location (Broglia, Schnebel et al. 2010), and weighted

principal component score (similar to the HIT severity profile: HITsp) (Greenwald, Gwin et al. 2008). There appears to be no cumulative effect of prior non-concussive impacts on the injury threshold (Eckner, Sabin et al. 2011). There has been no identified concussive injury threshold, with the main limitation being the small number of concussions that occur over the course of a data collection period that does not allow for sufficient statistical evidence.

Prevention

Although the direct role of linear and angular accelerations on head impact severity is not entirely clear, it is thought that the ability to dissipate these forces would decrease an athlete's risk of sustaining a concussion. It is believed that addressing factors related to an athlete's ability to dissipate force could be used as a means of prevention. It appears there are many factors that may affect the body's ability to withstand head impact forces, including appropriate protective equipment, muscular strength, and anticipation (Guskiewicz and Mihalik 2011).

While many studies discuss the role of anticipation and suggest a possible link to biomechanics and thus prevention, the role of collision anticipation in head impacts has not been extensively studied in college football players. One study followed youth ice hockey players wearing helmets instrumented with the HIT System and found that anticipated collisions resulted in less severe head impacts than unanticipated collisions, while open-ice collisions resulted in greater head linear and rotational accelerations than collisions along the playing boards (Mihalik, Blackburn et al. 2010). This study shows

that there is a possibility for anticipation to be addressed as a means of prevention, and more research is needed to be able to apply this concept to other sports.

In order to use anticipation as a means of prevention, we need to determine which aspects of anticipation in sport can be best observed, measured, and thus modified.

Cervical muscle strength is one aspect of anticipation that researchers have begun to investigate. Cervical muscle strengthening could decrease the risk of concussion based on the principal that tensing the cervical musculature increases the effective movable mass of the head, neck, and torso, thus increasing the ability to overcome the force of a possibly injurious head impact (Mihalik, Guskiewicz et al. 2011). While it is commonly mentioned during the discussion of anticipation in athletics, there is little research on the ability to quantify cervical muscle strength in dynamic on-field situations. One study investigated the relationship between cervical muscle strength and head impact biomechanics in youth ice hockey players and found no significant relationships (Mihalik, Guskiewicz et al. 2011). The current standard for measuring cervical muscle strength is a laboratory “break test” using a handheld dynamometer. The ability to transfer these measurements to make connections to on-field dynamic cervical muscle strength is not yet known. Until we can develop a more sport-appropriate way to measure cervical muscle strength in athletes, we must continue to look at other factors of anticipation that perhaps we can more accurately measure.

Another factor that may influence anticipation and affect an individual’s ability to withstand head impact forces is their level of visual and sensory performance. The brain receives sensory information from the eyes, integrates that with somatosensory and vestibular input from other sensors, and produces an appropriate motor response.

Individuals with higher levels of visual and sensory performance, including the characteristics of visual acuity and contrast sensitivity, are able to respond to their environment in a more efficient and appropriate way (Zimmerman, Lust et al. 2011). Much of the previous research on visual and sensory performance in athletics has focused on identifying differences between experts and novices or athletes and non-athletes. Some aspects that have been addressed by researchers include visual search behavior and fixation patterns. Experts tend to have more pertinent search strategies and more frequent fixations of shorter duration early on in the task (Williams, Davids et al. 1994; Martell and Vickers 2004), giving themselves just enough time to extract the appropriate information (Savelsbergh, Van der Kamp et al. 2005). A fixation of longer duration on a particular target may limit an athlete's ability to anticipate and prepare for an impending impact (Van der Kamp 2011).

Early research of visual and sensory performance used closed skills such as computerized or pen and paper laboratory tests. Researchers are realizing the importance of using more open skills in order to make their results more transferable to athletics. Studies involving soccer (Williams, Davids et al. 1994) and ice hockey (Martell and Vickers 2004) athletes have started incorporating open skill assessments. The Nike SPARQ Sensory Station is an evaluation and training tool of visual and sensory performance for athletes that could easily be used in a clinical setting. This program uses sport-relevant assessment tools that have the potential to be more applicable to athletics than small-screen computerized or pen and paper tests. It comprises tests to evaluate the following ten components of visual and sensory performance. See Table 2.1 for complete description of tests.

If an athlete is found to have deficits on certain components of the test, then the Nike SPARQ Sensory Station can be used as a training tool to improve identified deficits. It is quite possible that the level of visual and sensory performance identified by the Nike SPARQ Sensory Station is not only related to the athletic performance, but is also related to anticipation and level of awareness on the field.

Anticipation is a commonly discussed factor throughout the current research in visual and sensory performance. However, despite the identified relationship between collision anticipation and head impact severity in youth ice hockey players (Mihalik, Blackburn et al. 2010), there has been little research on the interaction between visual and sensory performance and head impact biomechanics in athletes. Visual training in the following areas: extent of visual fields, fields of recognition, accuracy of depth perception, and dynamic visual acuity, has been found to be transferable to the performance of athletes (Stine, Arterburn et al. 1982). This suggests that there may be a way to use visual and sensory performance training as a means of injury prevention, if we can identify a relationship between visual and sensory performance and head impact biomechanics and can find an appropriate way to identify at-risk athletes with low levels of visual and sensory performance.

Reaction time is one aspect of visual and sensory performance and there are currently many different measurement methods utilized throughout clinical settings. These tests could have potential to be added as part of an evaluation of an individual's level of visual and sensory performance, depending on the resources available to clinicians in various settings. It is believed that the functional impairments associated with prolonged reaction time could put an athlete at increased risk for an injurious head

impact (Eckner, Lipps et al. 2011). As an adjunct to the Nike SPARQ Sensory Station, these tests could provide a more sensitive way to identify athletes with low levels of visual and sensory performance who could be more at risk to sustain injurious head impacts.

Reaction time is defined as the elapsed time between the presentation of a sensory stimulus and the associated motor or behavioral response (Vickers 2007). There are two types of reaction time: simple and choice. Simple reaction time involves a situation where there is only one response option. Choice reaction time involves a situation where there is more than one response option. Reaction time has been found to be trainable in a group of experiments that showed there was a practice effect and a carryover of that practice effect after a three week period (Ando, Kida et al. 2001; Ando, Kida et al. 2002; Ando, Kida et al. 2004). These results show the potential of using tests of reaction time to identify individuals with deficits who could benefit from training.

Traditional measures of reaction time include computerized tests and the Clinical Reaction Time Apparatus. The Nike SPARQ Sensory Station can also be used to evaluate reaction time. There is little research on the relationship between the various measures of reaction time. If we can determine the relationship between these different measures we can develop the best way to evaluate reaction time to be able to better identify athletes with deficits in this aspect of visual and sensory performance.

CNS Vital Signs is a computerized neurocognitive test that was developed as a routine screening tool. It includes seven tests: verbal and visual memory, finger tapping, symbol digit coding, the Stroop Test, a test of shifting attention, and the continuous performance test. Performance on these tests provide a basis for scoring on ten clinical

domains: neurocognitive index (NCI), verbal memory standard score, visual memory standard score, processing speed standard score, executive function standard score, psychomotor speed standard score, reaction time standard score, complex attention standard score, and cognitive flexibility standard score (Gualtieri and Johnson 2006). Our study will only use the Stroop Test, as it is the only test required to calculate the clinical domain of reaction time.

Automated Neuropsychological Assessment Metrics (ANAM) is a computerized neurocognitive assessment tool that was developed by the United States Military's Office of Military Performance Assessment Technology (Kabat, Kane et al. 2001). Our study will only use the simple reaction time and procedural reaction time tests.

The Clinical Reaction Time Apparatus was developed to give clinicians a simple and inexpensive measure of reaction time that could be used on the sideline or in an athletic training room. This device is a thing, rigid cylinder with a weighted disk attached to the bottom. The examiner holds and releases the apparatus while the individual reacts and catches it as quickly as possible using a pinch grip. Performance on the Clinical Reaction Time Apparatus has been found to be correlated with computerized measures of reaction time, but has not yet been compared to other functional measures such as the Nike SPARQ Sensory Station (Eckner, Kutcher et al. 2010). The Clinical Reaction Time Apparatus has been correlated with performance on a functional sport-related head protective reaction time, in which subjects use both hands to block a foam tennis ball that was fired directly at their face. Reaction time on the Clinical Reaction Time Apparatus tended to be faster than the sport-related protective reaction time, but

there was a correlation between the two performance measures (Eckner, Lipps et al. 2011).

The Nike SPARQ Sensory Station tests reaction time as one of the ten components addressed in the evaluation. The large touch screen creates a test that measures reaction time in a more functional and athlete-friendly way. This system could easily be used in a clinical setting, and also be used as part of a training program if an athlete is found to have a deficit in their skill level of reaction time.

There are identified advantages to traditional measures of reaction time. Computerized tests have a few advantages over functional measures of reaction time. The software allows for consistency in the administering and scoring of tests, the ability to generate multiple forms of tests, the ability to track components of responses, efficiency in testing a large number of subjects, and the ability to contribute to large databases for normative data (Gualtieri and Johnson 2006). The Clinical Reaction Time Apparatus provides a simple and inexpensive and could be an appropriate option for a clinician with a limited budget (Eckner, Lipps et al. 2011).

The Nike SPARQ Sensory Station may have an advantage of being a more functional test of reaction time. It is designed to include sport-relevant and athlete friendly assessments. These tests are often believed to be more intrinsically motivating than computerized neuropsychological tests (Eckner, Kutcher et al. 2010). It may be that these functional tests more closely relate to the type of situations these athletes will see on the field and for that reason they have the potential to be more accurate representations of an athlete's true level of reaction time and thus ability to react to an impending head impact. Identifying relationships between traditional measures of

reaction time and visual sensory reaction time as measured by the Nike SPARQ Sensory Station, we will be better positioned to develop more appropriate testing batteries to evaluate an athlete's level of visual and sensory performance to be used for injury prevention interventions.

Rationale for Study

Developing strategies to prevent concussions is critical yet difficult due to the lack of knowledge of the exact mechanism of concussion. The role of anticipation in head impacts has been studied in other populations, but has not been extensively studied in collegiate football players. It is quite possible that the level of visual and sensory performance is not only related to the athlete's performance on the field, but is also related to anticipation and level of awareness of impending head impacts during athletic competition.

If there is a relationship between level of visual and sensory performance, collision anticipation, and head impact biomechanics, then visual and sensory function evaluation and training devices could be used to identify at-risk athletes and create interventions to hopefully decrease their overall risk of injurious head impacts. Further, if we can determine the relationship between traditional measures of reaction time and reaction time as measured by the Nike SPARQ Sensory Station we can develop the most appropriate testing battery to assess an athlete's level of visual and sensory performance that could be used to create a more effective preventative measure.

Therefore, the purpose of this study was to 1) determine the relationship between traditional measures of reaction time and reaction time as measured by the Nike SPARQ

Sensory Station, 2) determine the association between level of visual and sensory performance and head impact severity in college football players, and 3) determine the association between collision anticipation and head impact severity in college football players.

Table 2.1. Nike SPARQ Sensory Station Evaluation

Test	Description	Participant Set-Up	Procedures
Visual Break	A test of visual endurance.	Examiner holds a 24-cm ruler up with the base in between the subject's eyes. The ruler has a sliding component with a single black line in the subject's field of vision.	Prior to beginning the Nike SPARQ Sensory Station Evaluation, the subject will complete the visual break test. The sliding piece is started at the maximal distance from the subject's eyes, and slowly moved closer. The subject is instructed to focus on the line for as long as possible, until it begins to blur or split to two black lines.
Visual Clarity	How clearly athletes see distant details.	Participant stands 16 ft from a 22-in display holding iPod Touch	Black Landolt rings (C-shaped ring) with gaps at the top, bottom, left, and right will appear in random order on a white background. Participants are instructed to swipe the iPod touch screen in the direction of the gap of the Landolt ring. The rings are preset at varying acuity demands. The procedures include binocular and monocular assessments. The examiner will isolate each eye with a vision occluder.
Contrast Sensitivity	Ability to pinpoint subtle differences in contrast.	Participant stands 16 ft from a 22-in display holding iPod Touch	Four black circles are presented on a light background. At random, one of the circles will contain a pattern of rings. Participants were instructed to swipe the iPod touch screen in the direction of the circle with the ring pattern.
Depth Perception	Speed and accuracy in judging 2-eyed depth information through multiple gaze positions.	Participant stands 16 ft from a 22-in display holding iPod Touch wearing liquid crystal goggles (NVIDIA 3D Vision, Santa Clara, CA)	The goggles create a simulated depth in one of the four rings that will appear on the screen. The participant is instructed to swipe the iPod touch screen in the direction of the ring that appears closer.
Near-Far Quickness	Quickly & accurately change visual attention between near and far distances.	Participant stands 16 ft from a 22-in display holding the iPod touch's top edge with the far display's bottom.	A black Landolt ring will be presented alternating between the iPod touch screen and the screen on Nike SPARQ Sensory Station display. The participant is instructed to swipe the iPod touch screen in the direction of the gap of the Landolt ring.
Target Capture	Ability for rapid visual shifting and recognition of peripheral targets.	Participant stands 16 feet away from 42-inch display holding iPod Touch	The participant will focus on a central white dot until a Landolt ring appears briefly in one of the corners on the Nike SPARQ Sensory Station display. The participant is instructed to swipe in the direction of the gap of the Landolt ring.
Perception Span	Visual quickness in acquiring critical information.	Participant stands within arm's length of 42-inch display with center of screen adjusted to their height.	The participant will focus on a dot in the center of a grid pattern composed of up to 30 circles. A pattern of dots will flash within the grid. The participant will use the touch screen to recreate the pattern of dots.
Eye-Hand Coordination	Ability to make quick and accurate visually-guided hand responses to rapidly changing targets.	Participant holds arms parallel to ground at shoulder height within arm's length of 42-inch display that is adjusted to their height.	A grid will be presented with eight columns and six rows of equally sized and spaced circles. A dot will appear within one circle of the grid. Participant will be instructed to touch the dot as quickly as possible with either hand. As soon as they touch the dot, another dot will be presented. 96 dots will appear in a pseudorandomized sequence.
Decision Making (Go/No-Go)	Quick & accurate decision responses to rapidly changing targets.	Participant holds arms parallel to ground at shoulder height within arm's length of 42-in display.	An identical grid as Eye-Hand Coordination test appears. A green or red dot will appear. If the dot is green, the participant is instructed to touch it. If the dot is red, the participant is instructed not to touch it. 96 dots will appear in a pseudorandomized sequence.
Reaction Time	Speed and quickness of an athlete's hand reaction in response to a visual stimulus.	Participant stands within arm's length of 42-inch display with center of screen adjusted to their height.	Two annular patterns appear on the screen. Participant places dominant hand fingertips on inner circle of pattern. This changes circle to green. Participant focuses on the center of the annular pattern in front of them. After a random delay of 2, 3, or 4 sec, the second pattern turns green and athlete moves their hand to touch its inner circle as quickly as possible.

CHAPTER III

METHODOLOGY

Participants

We recruited 38 Division I college football players from the University of North Carolina at Chapel Hill Fall 2012 football team (age = 20.4 ± 1.4 years; height = 190.2 ± 6.7 cm; mass = 109.3 ± 17.8 kg). Participants were selected based on input from the coaching and sports medicine staff to include a variety of player positions including 2 quarterbacks, 3 wide receivers, 3 offensive backs, 12 offensive linemen (including tight ends), 12 defensive backs (including linebackers), and 6 defensive linemen. All participants signed an informed consent approved by the University of North Carolina's Institutional Review Board prior to participation in study. Inclusion criteria required that participants must be a University of North Carolina at Chapel Hill Division I collegiate football player during the Fall 2012 season, who wore a helmet equipped with the Head Impact Telemetry System, and consented to the study. Exclusion criteria included anyone who has a history of permanent vision loss or is currently symptomatic from a head, neck, or eye injury that would negatively affect scores on visual and sensory performance tasks.

Instrumentation

Head Impact Telemetry System

The Head Impact Telemetry System (Simbex, Lebanon, NH) was used to collect data on linear acceleration, rotational acceleration, and Head Impact Technology severity profile (HITsp). The HIT System is comprised of six spring-loaded single-axis accelerometers inserted into Riddell VSR4 (sizes: L or XL), Revolution (sizes: M, L, or XL), or Revolution Speed (sizes: M, L, or XL) football helmets (Riddell Corporation) and the Sideline Response System. The in-helmet accelerometers are strategically placed to allow for measurement of linear and rotational acceleration and impact location. Up to 100 separate head impacts can be stored in the memory built into the accelerometer. The accelerometers collect data at 1 kHz for a period of forty milliseconds; eight milliseconds are recorded before the data collection trigger and thirty-two milliseconds of data are collected after the trigger. The HIT System can collect data from up to 64 players over a distance greater than the length of a football field.

The Sideline Response System was located on the sideline during games and practices. This unit receives time-stamped, encoded data from the in-helmet accelerometers through a radiofrequency telemetry link. The data are processed through a novel algorithm to determine location and magnitude of impacts (Crisco, Chu et al. 2004). The user can access these data through the Head Impact Telemetry Impact Analyzer software on laptop in the Sideline Response System unit. The HIT System measures linear acceleration (measured in terms of gravitational acceleration, g), rotational acceleration (measured in rad/s^2), and Head Impact Technology severity profile

(HITsp). The HITsp is a weighted composite score encompassing linear and rotational accelerations, Gadd Severity Index, Head Injury Criterion, and impact location. The HIT System is a valid measure of head impact biomechanics (Duma, Manoogian et al. 2005).

Visual and Sensory Performance Assessment

The Nike SPARQ Sensory Station is an evaluation and training tool of visual and sensory performance designed for athletes. The Nike SPARQ Sensory Station is an interactive touch screen device consists of a single computer that controls two high-resolution LCD monitors (one twenty-two inch and one forty-two inch monitor). An Apple iPod touch is also used for some of the assessments (Erickson, Citek et al. 2011). See Table 2.1 for description and testing procedures for each evaluation component.

The Nike SPARQ Sensory Station has been found to be a reliable measure of visual and sensory performance with no significant changes in performance between multiple sessions on visual clarity, contrast sensitivity, depth perception, target capture, perception span, and reaction time. However, an expected learning effect was found for performance on Near-Far Quickness, Eye-Hand Coordination and Go/No Go across two testing sessions separated by a period of about one week (Erickson, Citek et al. 2011).

Reaction Time Assessments

The subjects underwent a series of reaction time assessments including the computerized tests CNS Vital Signs and Automated Neuropsychological Assessment Metrics (ANAM), and the Clinical Reaction Time Apparatus. The Nike SPARQ Sensory Station also includes a test of reaction time. Subjects completed the entire test on the Nike SPARQ Sensory Station, but reaction time scores were used in the comparison to the previously mentioned assessments.

CNS Vital Signs (CNS Vital Signs, LLC, Chapel Hill, NC) is a series of computerized neurocognitive tests that can detect changes in neurocognitive performance over time. Participants only completed the Stroop test, which measures the ability to react to a simple, but increasingly difficult set of directions. See Table 3.1 for a complete description of the procedures for this test. The reaction time domain score is calculated using the following equation: $[\text{Stroop Test (ST) Complex Reaction Time Correct} + \text{Stroop Reaction Time Correct}] / 2$. CNS Vital Signs has been found to be valid and reliable (Gualtieri and Johnson 2006).

Automated Neuropsychological Assessment Metrics (Vista LifeSciences, Washington D.C.) is a series of computerized neurocognitive tests that was developed by the United States Military's Office of Military Performance Assessment Technology to detect changes in neurocognitive performance overtime. (Kabat, Kane et al. 2001). Our study used the simple reaction time test, in which the individual is instructed to press the mouse key upon the presentation of a simple stimulus of an asterisk on the screen. Our study also used the procedural reaction time test, in which the individual is tested on both reaction time and processing speed. The individual is presented with one of the numerals 2, 3, 4, and 5 and respond by clicking the left mouse button if the stimulus is a 2 or 3 and clicking the right mouse button if the stimulus is a 4 or 5. ANAM has been found to be valid and reliable (Kabat, Kane et al. 2001; Segalowitz, Mahaney et al. 2007).

The Clinical Reaction Time Apparatus was developed to give clinicians a simple and inexpensive measure of reaction time that could be used on the sideline or in an athletic training room. This device is a thin, rigid cylinder with a weighted disk attached to the bottom. The examiner holds and releases the apparatus while the individual reacts

and catches it as quickly as possible using a pinch grip. Subjects completed two practice trials followed by eight trials in which the examiner released the apparatus at pre-determined randomized time intervals ranging from two to five seconds. The examiner noted the measured distance at which the most superior portion of the subject's pinch grip makes contact with the apparatus. A trial in which the subjects dropped the apparatus was noted as a "drop" and was not included as part of the calculation of clinical reaction time. The Clinical Reaction Time Apparatus has been found to be a valid and reliable measure of reaction time (Eckner, Whitacre et al. 2009).

Video Evaluation

The retrospective analysis of collision anticipation used previously analyzed video footage and head impact biomechanical data from the Fall 2010 season. Impacts were evaluated using the Player-to-Player Collision Type Evaluation Form that we developed for our previous research in this area. Intrarater reliability was tested by selecting and evaluating a subset of cases using the form, and then re-evaluating them thirty days after initial evaluation ($k=.88$) (Ocwieja, Mihalik et al. 2012). The Player-to-Player Collision Type Evaluation Form evaluates the following components: play type, closing distance, starting stance of player and opponent, whether the player was striking or being struck, whether the player was looking ahead or in the direction of the collision, ball possession, infraction type, movement of player and opponent, and overall impression of the level of anticipation based on these factors. (See Appendix A: The Player-to-Player Collision Type Evaluation Form).

Procedures

Subjects underwent a single testing at the beginning of the Fall 2012 season. A trained clinician administered the testing session in a quiet controlled environment at the Matthew Gfeller Sport-Related Traumatic Brain Injury Research Center (Chapel Hill, NC). All subjects completed the tests in a counterbalanced order and received standardized directions given by the administering clinician. The testing session took approximately 30-45 minutes. Subjects were not given any feedback regarding performance during the testing session. The testing session included the following assessments: Nike SPARQ Sensory Station, and reaction time tests on CNS Vital Signs, ANAM, and the Clinical Reaction Time Apparatus.

The team's professional equipment manager fit subjects with an MxEncoder-equipped Riddell helmet at the beginning of the Fall 2012 season. Head impact data were collected during practices and games throughout the course of the season. The HIT System and Sideline Response System were checked on a weekly basis and prior to all games and practices, to ensure proper functioning.

The retrospective analysis of collision anticipation used previously analyzed video footage and head impact biomechanical data from the Fall 2010 season. Video footage was collected during all games and was filmed from two positions on the field: sideline and end zone. During the Fall 2010 season, a research assistant was responsible for setting up a video camera to record the game clock during competition and for synchronizing the time to ensure that the video footage could be linked to the head impact biomechanical data. Video footage was analyzed using the Player-to-Player

Collision Type Evaluation Form. The principal investigator was blinded to the biomechanical data during impact video analysis to allow for an unbiased analysis. Each impact was categorized as anticipated or unanticipated and as mild, moderate or severe.

Data Reduction

For our first research question, we used data from the scores on traditional reaction time tests (CNS Vital Signs, ANAM, and Clinical Reaction Time Apparatus) and the reaction time component of the Nike SPARQ Sensory Station evaluation. These scores were analyzed using Pearson correlations to determine the relationship between traditional measures of reaction time and reaction time as measured by the Nike SPARQ Sensory Station. One participant sustained a season-ending injury during the first week of practices, and another participant replaced his helmet with one incapable of supporting the HIT System technology. For these reasons, we did not have sufficient head impact biomechanical data and only used the scores from the initial testing session towards answering our first research question. This created a sample size of 38 participants for our first research question and 36 participants for our second research question.

For our second research question, we used raw data on visual and sensory performance that was exported from the Nike SPARQ Sensory Station. Scores for each individual test and the overall composite score were analyzed. We categorized subjects into two groups based on their performance on each assessment of the Nike SPARQ Sensory Station (High level of performance: $\geq 51^{\text{st}}$ percentile; Low level of performance: $\leq 49^{\text{th}}$ percentile). These percentiles were based on our study's sample. The following assessments had approximately equal number of subjects scoring in high and low

performance groups, and thus were included in our analyses: Depth Perception, Near-Far Quickness, Target Capture, Perception Span, Eye Hand Coordination, Go/No Go, and Reaction Time. We also categorized subjects into high and low performance groups based on their performance on Visual Break and Reaction Time as measured by the Clinical Reaction Time Apparatus. Raw head impact data from the games and practices of the Fall 2012 season were exported from Sideline Response System using the Ridell Export Utility into Matlab 7 (The Mathworks, Inc., Natick, MA). Linear acceleration (g), rotational acceleration (rad/s^2), and HITsp were the outcome measures of interest. All impacts under 10 g were removed because they are considered negligible with respect to head impact biomechanics and injury (Mihalik, Bell et al. 2007).

In order to allow for comparisons with previous research in this area, we categorized the head impact severity based on linear acceleration as mild ($<66\text{g}$), moderate ($66\text{-}106\text{g}$), or severe ($>106\text{g}$) and based on rotational acceleration as mild ($<4600\text{g}$), moderate ($4600\text{-}7900\text{g}$), or severe ($>7900\text{g}$) for our chi-square analyses (Zhang, Yang et al. 2004; Ocwieja, Mihalik et al. 2011). We used the two levels of visual and sensory performance (high and low) and three levels of impact severity (mild, moderate, severe) for our chi-square analyses to determine the association between level of visual and sensory performance and head impact severity. The two levels of visual and sensory performance (high and low) were also used in linear mixed model ANOVAs to determine differences in head impact biomechanics between groups. Our third research question was retrospective. We used previously analyzed video footage from games played during the Fall 2010 season. The collisions were classified as unanticipated or anticipated based on the Player-to-Player Collision Type evaluation

form. Raw head impact data from the Fall 2010 season were exported from Sideline Response System using the Ridell Export Utility into Matlab 7 (The Mathworks, Inc., Natick, MA). Linear acceleration (g), rotational acceleration (rad/s^2), and HITsp were the outcome measures of interest. All impacts under 10 g were removed because they are considered negligible with respect to head impact biomechanics and injury (Mihalik, Bell et al. 2007). In order to allow for comparisons with previous research in this area, we categorized the head impact severity based on linear acceleration as mild ($<66\text{g}$), moderate ($66\text{-}106\text{g}$) or severe ($>106\text{g}$) for our chi-square analyses (Zhang, Yang et al. 2004; Ocwieja, Mihalik et al. 2011). We used two levels of collision anticipation (anticipated, unanticipated) and three levels of head impact severity (mild, moderate, severe) in our chi-square analyses to determine the association between level of collision anticipation and head impact severity.

Data Analyses

All data were analyzed using SAS 9.3 statistical software with an a priori alpha level of 0.05. Pearson correlational analyses were used to assess the relationship between traditional measures of reaction time and reaction time as measured by the Nike SPARQ Sensory Station. Three separate random intercepts general linear mixed models were fit for linear acceleration, rotational acceleration, and HITsp. The large number of low magnitude head impacts skewed the distribution of head impacts; therefore, we used the natural logarithmic transformations for linear acceleration, rotational acceleration, and HITsp to create a normal distribution for statistical analyses.

Prospective Chi-Square analyses were used to assess the association between level of visual and sensory performance (high and low) and an ordinal variable of impact severity (mild, moderate, severe) based on linear acceleration and rotational acceleration measures collected during head impacts that occurred during the Fall 2012 season. Linear mixed model ANOVAs were performed to analyze the differences in head impact biomechanics (linear acceleration, rotational acceleration, and HITsp) between high and low visual and sensory performers in each of the visual and sensory performance assessments.

Retrospective Chi-Square analyses were performed to assess the association between level of anticipation (anticipated, unanticipated) and an ordinal variable of impact severity (mild, moderate, severe) based on linear and rotational acceleration measures that were collected during head impacts that occurred during the Fall 2010 season. Fisher's Exact test was used in these Chi-Square analyses in order to account for the low number of unanticipated collisions.

Table 3.1. Data analysis plan

<u>Question</u>	<u>Description</u>	<u>Variables of Interest</u>	<u>Comparison</u>	<u>Method</u>
1 Prospective	Is there a significant correlation between computerized and functional measures of reaction time and reaction time as measured by the Nike SPARQ Sensory Station?	<u>Traditional Measures</u> <ul style="list-style-type: none"> CNS Vital Signs Reaction Time Domain ANAM Reaction Time Clinical Reaction Time Apparatus <u>Nike SPARQ Sensory Station</u> <ul style="list-style-type: none"> Reaction Time Test 	Performance on traditional measures Performance on Nike SPARQ Sensory Station reaction time test	Pearson Correlations
2 Prospective	Is there a significant association between level of visual and sensory performance and head impact severity in college football players?	<u>Nike SPARQ Sensory Station</u> <ul style="list-style-type: none"> Outcome measures (10) <u>HIT System</u> <ul style="list-style-type: none"> Linear Acceleration Rotational Acceleration HITsp 	Level of visual and sensory performance <ul style="list-style-type: none"> High level Low level Head impact severity <ul style="list-style-type: none"> Mild Moderate Severe 	Chi-Square Linear mixed model ANOVA
3 Retrospective	Is there a significant association between collision anticipation and head impact severity in college football players?	<u>Collision Anticipation</u> <ul style="list-style-type: none"> Anticipated Unanticipated <u>HIT System</u> <ul style="list-style-type: none"> Linear Acceleration Rotational Acceleration HITsp 	Level of anticipation <ul style="list-style-type: none"> Anticipated Unanticipated Head impact severity <ul style="list-style-type: none"> Mild Moderate Severe 	Chi-Square

Table 3.2. Stroop Test

Test Portion	Description
1	A color word will appear at the bottom of the screen in black font. Press the space bar as soon as you see a word appear on the screen.
2	A color word will appear at the bottom of the screen. Press the space bar as soon as you see the color of the word match what the word says
3	A color word will appear at the bottom of the screen. Press the space bar as soon as you see the color word does not match what the word says

CHAPTER IV

MANUSCRIPT

Introduction

Concussion has been defined as a complex pathophysiologic process affecting the brain, induced by traumatic biomechanical forces that typically result in an impairment of neurologic function and clinical symptoms such as disturbances of vision and equilibrium (McCrory, Meeuwisse et al. 2009). Sport-related concussions have become a major public health concern, with approximately 3.8 million sports-related traumatic brain injuries occurring in the United States each year (Langlois, Rutland-Brown et al. 2006). The majority of sport-related concussions occur in contact or collision sports such as football, which is one of the most popular sports among high school and collegiate males. (Bracken 2007; 2011). Sport-related concussions account for a high percentage of injuries at both the collegiate and high school level of football (Dick, 2007;Gessel, 2007).

Mechanisms of injury for concussions include both direct and indirect head impacts, (Guskiewicz and Mihalik 2011) resulting in a combination of two types of forces: linear and rotational (Bailes and Cantu 2001). The severity of a concussion is believed to be related to the magnitude, direction, and distribution of the forces applied to the brain (Guskiewicz and Mihalik 2011). It is thought that the ability to dissipate these linear and angular acceleration forces associated with high magnitude impacts would decrease a person's risk of sustaining a concussion. Researchers have studied collision

anticipation in an attempt to understand the causes and factors related to concussion. Anticipated collisions are associated with less severe head impacts in youth ice hockey players (Mihalik, Blackburn et al. 2010); however, this has not been extensively studied in collegiate football players. Visual and sensory performance, referring to the manner the brain receives sensory information from the eyes, integrates that with somatosensory and vestibular input from other sensors, and produces an appropriate motor response, may influence anticipation and affect an individual's ability to withstand head impact forces. Individuals with higher levels of visual and sensory performance, including the characteristics of visual acuity and contrast sensitivity, are able to respond to their environment in a more efficient and appropriate way (Zimmerman, Lust et al. 2011). Visual training has been found to be transferable to the performance of athletes (Stine, Arterburn et al. 1982). Several tools exist to evaluate and train components of an individual's level of visual and sensory performance. An athlete's visual and sensory performance may not only be relevant to performance but also to their ability to anticipate and react to impending head impacts on the field, ushering in a new area of research with the goal of preventing injury while concurrently improving athlete performance.

Evaluation of visual and sensory performance may be implemented to identify at-risk athletes, and lead to prospective interventions designed to decrease an athlete's overall risk of sustaining injurious head impacts. In addition, an evaluation of visual and sensory performance includes an assessment of an athlete's functional reaction time, traditionally using computerized neurocognitive tests that are far dissimilar to the reaction time demands that are ultimately experienced by athletes in their sports.

Identifying the relationships between traditional measures of reaction time and visual sensory reaction time as measured by the Nike SPARQ Sensory Station will provide insight regarding the development of more appropriate testing batteries to evaluate an athlete's level of visual and sensory performance to be used for injury prevention interventions. Therefore, the threefold purpose of this study was to determine: 1) the relationship between traditional measures of reaction time and reaction time as measured by the Nike SPARQ Sensory Station, 2) the association between level of visual and sensory performance and head impact severity in college football players, and 3) the association between collision anticipation and head impact severity in college football players.

Methods

Participants

We recruited 38 Division I college football players from the University of North Carolina at Chapel Hill Fall 2012 football team (age = 20.4 ± 1.4 years; height = 190.2 ± 6.7 cm; mass = 109.3 ± 17.8 kg). Participants were selected based on input from the coaching and sports medicine staff to include a variety of player positions including 2 quarterbacks, 3 wide receivers, 3 offensive backs, 12 offensive linemen (including tight ends), 12 defensive backs (including linebackers), and 6 defensive linemen. All participants signed an informed consent form approved by the university institutional review board prior to participation in the study. Inclusion criteria required that participants must be a Division I collegiate football player during the Fall 2012 season, who wore a helmet equipped with the Head Impact Telemetry System, and consented to

participating in the study. Exclusion criteria included anyone who had a history of permanent vision loss or was currently symptomatic from a head, neck, or eye injury that would have negatively affected scores on visual and sensory performance tasks.

Instrumentation

Head Impact Telemetry System

The Head Impact Telemetry System (Simbex, Lebanon, NH) was used to collect helmet linear acceleration, rotational acceleration, and Head Impact Technology severity profile (HITsp) data. The HIT System is comprised of six spring-loaded single-axis accelerometers inserted into Riddell VSR4 (sizes: L or XL), Revolution (sizes: M, L, or XL), or Revolution Speed (sizes: M, L, or XL) football helmets (Riddell Corporation) and the Sideline Response System. The in-helmet accelerometers are strategically placed to allow for measurement of linear and rotational acceleration and impact location. Up to 100 separate head impacts can be stored in the on-board memory built into the accelerometer. The accelerometers collect data at 1 kHz for a period of forty milliseconds; eight milliseconds are recorded before the data collection trigger and thirty-two milliseconds of data are collected after the trigger. The HIT System can collect data from up to 64 players over a distance greater than the length of a football field.

The Sideline Response System was located on the sideline during games and practices. This unit receives time-stamped, encoded data from the in-helmet accelerometers through a radiofrequency telemetry link. The data are processed through a novel algorithm to determine location and magnitude of impacts (Crisco, Chu et al. 2004). The user can access these data through the Head Impact Telemetry Impact Analyzer software on laptop in the Sideline Response System unit. The HIT System

measures linear acceleration (measured in terms of gravitational acceleration, g), rotational acceleration (measured in rad/s^2), and Head Impact Technology severity profile (HITsp). The HITsp is a weighted composite score encompassing linear and rotational accelerations, Gadd Severity Index, Head Injury Criterion, and impact location. The HIT System is a valid measure of head impact biomechanics (Duma, Manoogian et al. 2005).

Visual and Sensory Performance Assessment

The Nike SPARQ Sensory Station is an evaluation and training tool of visual and sensory performance designed for athletes. The Nike SPARQ Sensory Station is an interactive touch screen device consisting of a single computer that controls two high-resolution LCD monitors (one twenty-two inch and one forty-two inch monitor). An Apple iPod Touch is also used for some of the assessments (Erickson, Citek et al. 2011). See Table 2.1 for description and testing procedures for each evaluation component. The Nike SPARQ Sensory Station has been found to be a reliable measure of visual and sensory performance with no significant changes in performance between multiple sessions on visual clarity, contrast sensitivity, depth perception, target capture, perception span, and reaction time. However, an expected learning effect was found for performance on Near-Far Quickness, Eye-Hand Coordination and Go/No Go across two testing sessions separated by a period of about one week (Erickson, Citek et al. 2011).

Reaction Time Assessments

The subjects underwent a series of reaction time assessments including the computerized tests CNS Vital Signs and Automated Neuropsychological Assessment Metrics (ANAM), and the Clinical Reaction Time Apparatus. The Nike SPARQ Sensory Station also includes a test of reaction time. Subjects completed the entire test on the

Nike SPARQ Sensory Station, but reaction time scores were used in the comparison to the previously mentioned assessments.

CNS Vital Signs (CNS Vital Signs, LLC, Chapel Hill, NC) consists of a series of computerized neurocognitive tests capable of detecting changes in neurocognitive performance over time. Participants only completed the Stroop test, which measures the ability to react to a simple, but increasingly difficult set of directions. See Table 3.1 for a complete description of the procedures for this test. The reaction time domain score is calculated using the following equation: $[\text{Stroop Test (ST) Complex Reaction Time Correct} + \text{Stroop Reaction Time Correct}] / 2$. CNS Vital Signs has been found to be valid and reliable (Gualtieri and Johnson 2006).

Automated Neuropsychological Assessment Metrics (Vista LifeSciences, Washington D.C.) is a series of computerized neurocognitive tests that was developed by the United States Military's Office of Military Performance Assessment Technology to detect changes in neurocognitive performance overtime. (Kabat, Kane et al. 2001). Our study used the simple reaction time test, in which the individual is instructed to press the mouse key upon the presentation of a simple stimulus of an asterisk on the screen. Our study also used the procedural reaction time test, in which the individual is tested on both reaction time and processing speed. The individual is presented with one of the numerals 2, 3, 4, and 5 and respond by clicking the left mouse button if the stimulus is a 2 or 3 and clicking the right mouse button if the stimulus is a 4 or 5. ANAM has been found to be valid and reliable (Kabat, Kane et al. 2001; Segalowitz, Mahaney et al. 2007).

The Clinical Reaction Time Apparatus was developed to give clinicians a simple and inexpensive measure of reaction time that could be used on the sideline or in an

athletic training room (Eckner, Whitacre et al. 2009). This device is a thin, rigid cylinder with a weighted disk attached to the bottom. The examiner holds and releases the apparatus while the individual reacts and catches it as quickly as possible using a pinch grip. Subjects completed two practice trials followed by eight trials in which the examiner released the apparatus at pre-determined randomized time intervals ranging from two to five seconds. The examiner noted the measured distance at which the most superior portion of the subject's pinch grip makes contact with the apparatus. A trial in which the subjects dropped the apparatus was noted as a "drop" and was not included as part of the calculation of clinical reaction time. The Clinical Reaction Time Apparatus has been found to be a valid and reliable measure of reaction time (Eckner, Whitacre et al. 2009).

Video Evaluation

The retrospective analysis of collision anticipation used previously analyzed video footage and head impact biomechanical data from the Fall 2010 season. Impacts were evaluated using the Player-to-Player Collision Type Evaluation Form that we developed for our previous research in this area. Intrarater reliability was tested by selecting and evaluating a subset of cases using the form, and then re-evaluating them thirty days after initial evaluation (Kappa = 0.88) (Ocwieja, Mihalik et al. 2012). The Player-to-Player Collision Type Evaluation Form evaluates the following components: play type, closing distance, starting stance of player and opponent, whether the player was striking or being struck, whether the player was looking ahead or in the direction of the collision, ball possession, infraction type, movement of player and opponent, and

overall impression of the level of anticipation based on these factors. (See Appendix A: The Player-to-Player Collision Type Evaluation Form).

Procedures

Subjects underwent a single testing at the beginning of the Fall 2012 season. A trained clinician administered the testing session in a quiet controlled environment in our clinical research center. All subjects completed the tests in a counterbalanced order and received standardized directions given by the administering clinician. The testing session took approximately 30-45 minutes. Subjects were not given any feedback regarding performance during the testing session. The testing session included the following assessments: Nike SPARQ Sensory Station, and reaction time tests on CNS Vital Signs, ANAM, and the Clinical Reaction Time Apparatus.

The team's professional equipment manager fit subjects with an MxEncoder-equipped Riddell helmet at the beginning of the Fall 2012 season. Head impact data were collected during practices and games throughout the course of the season. The HIT System and Sideline Response System were checked on a weekly basis and prior to all games and practices, to ensure proper functioning.

The retrospective analysis of collision anticipation used previously analyzed video footage and head impact biomechanical data from the Fall 2010 season. Video footage was collected during all games and was filmed from two positions on the field: sideline and end zone. During the Fall 2010 season, a research assistant was responsible for setting up a video camera to record the game clock during competition and for synchronizing the time to ensure that the video footage could be linked to the head

impact biomechanical data. Video footage was analyzed using the Player-to-Player Collision Type Evaluation Form. The principal investigator was blinded to the biomechanical data during impact video analysis to allow for an unbiased analysis. Each impact was categorized as anticipated or unanticipated and as mild, moderate or severe.

Data Reduction

For our first research question, we used data from the scores on traditional reaction time tests (CNS Vital Signs, ANAM, and Clinical Reaction Time Apparatus) and the reaction time component of the Nike SPARQ Sensory Station evaluation. These scores were analyzed using Pearson correlations to determine the relationship between traditional measures of reaction time and reaction time as measured by the Nike SPARQ Sensory Station.

For our second and third research questions, raw head impact data were exported from Sideline Response System using the Ridell Export Utility into Matlab 7 (The Mathworks, Inc., Natick, MA). Linear acceleration (g), rotational acceleration (rad/s^2), and HITsp were the outcome measures of interest. All impacts under 10 g were removed because they are considered negligible with respect to head impact biomechanics and injury (Mihalik, Bell et al. 2007). In order to allow for comparisons with previous research in this area, we categorized the head impact severity for linear acceleration as mild ($<66\text{g}$), moderate ($66\text{-}106\text{g}$) or severe ($>106\text{g}$) and for rotational acceleration as mild ($<4600\text{g}$), moderate ($4600\text{-}7900\text{g}$), or severe ($>7900\text{g}$) (Zhang, Yang et al. 2004; Ocwieja, Mihalik et al. 2011).

For our second research question, we also used data from the Nike SPARQ Sensory Station and reaction time as measured by the Clinical Reaction Time Apparatus. Raw data on visual and sensory performance was exported from the Nike SPARQ Sensory Station, including scores for Visual Break, Depth Perception, Near-Far Quickness, Target Capture, Perception Span, Eye Hand Coordination, Go/No Go, and Reaction Time. We categorized subjects into two groups based on their performance on each measure (High level of performance: $\geq 51^{\text{st}}$ percentile; Low level of performance: $\leq 49^{\text{th}}$ percentile). These percentiles were based on our study's sample. We also used raw head impact data from the games and practices of the Fall 2012 season. We used the two levels of visual and sensory performance (high and low) and three levels of impact severity (mild, moderate, severe) for our chi-square analyses to determine the association between level of visual and sensory performance and head impact severity. The two levels of visual and sensory function (high and low) were also used in linear mixed model ANOVAs to determine differences in head impact biomechanics between groups.

Our third research question was retrospective, and used previously analyzed video footage and raw head impact data from games played during the Fall 2010 season. The collisions were classified as unanticipated or anticipated based on the Player-to-Player Collision Type evaluation form; these measures were categorized as described above (Zhang, Yang et al. 2004; Ocwieja, Mihalik et al. 2011). We used two levels of collision anticipation (anticipated, unanticipated) and three levels of head impact severity (mild, moderate, severe) in our chi-square analyses to determine the association between level of collision anticipation and head impact severity.

Data Analyses

All data were analyzed using SAS 9.3 statistical software with an a priori alpha level of 0.05. Pearson product-moment correlation coefficients were calculated between traditional measures of reaction time and reaction time as measured by the Nike SPARQ Sensory Station. Three separate random intercepts general linear mixed models were fit for linear acceleration, rotational acceleration, and HITsp. The large number of low magnitude head impacts skewed the distribution of head impacts; therefore, we used the natural logarithmic transformations for linear acceleration, rotational acceleration, and HITsp to create a normal distribution for statistical analyses.

Prospective Chi-Square analyses were used to assess the association between level of visual and sensory performance (high and low) and an ordinal variable of impact severity (mild, moderate, severe) based on linear acceleration and rotational acceleration measures collected during head impacts that occurred during the Fall 2012 season. Linear mixed model ANOVAs were performed to analyze the differences in head impact biomechanics (linear acceleration, rotational acceleration, and HITsp) between high and low visual and sensory performers.

Retrospective Chi-Square analyses were performed to assess the association between level of anticipation (anticipated, unanticipated) and a ordinal variable of impact severity (mild, moderate, severe) based on linear and rotational acceleration measures that were collected during head impacts that occurred during the Fall 2010 season. Fisher's Exact test was used in these Chi-Square analyses in order to account for the low number of unanticipated collisions.

Results

One participant sustained a season-ending injury during the first week of practices, and another participant replaced his helmet with one incapable of supporting the HIT System technology. For these reasons, we did not have sufficient head impact biomechanical data and only used the scores from the initial testing session towards answering our first research question. This created a sample size of 38 participants for our first research question and 36 participants for our second research question.

Reaction Time

The CNS Vital Signs reaction time raw score was significantly associated with ANAM simple reaction time ($r = -0.328$; $P = 0.044$) and procedural reaction time ($r = -0.330$; $P = 0.043$) throughput scores. Due to the nature of the data, the negative relationship indicates that as ANAM simple and procedural reaction time throughput scores increases (indicating better performance), reaction time scores likewise improved on CNS Vital Signs as a result of a decrease in the milliseconds necessary to complete the task. We did not observe any significant correlations between reaction time measures on the computerized reaction time tests and the Clinical Reaction Time Apparatus or the Nike SPARQ Sensory Station. We also did not observe a significant correlation between reaction time measures on the Clinical Reaction Time Apparatus and the Nike SPARQ Sensory Station ($P > 0.05$ for all).

Visual and Sensory Performance

We observed a significant association between a categorized variable of head impact severity based on linear acceleration and level of visual and sensory performance on the following assessments: Reaction Time as measured by the Nike SPARQ Sensory

Station ($\chi^2[2] = 21.166, P < 0.001$), Target Capture ($\chi^2[2] = 44.572, P < 0.001$), Near-Far Quickness ($\chi^2[2] = 10.042, P = 0.007$), Depth Perception ($\chi^2[2] = 11.852, P = 0.003$), and Go/No Go ($\chi^2[2] = 12.092, P = 0.002$). We observed a significant association between a categorized variable of head impact severity for rotational acceleration and level of visual and sensory performance on the following assessments: Reaction Time as measured by the Nike SPARQ Sensory Station ($\chi^2[2] = 25.187, P < 0.001$), Reaction Time as measured by the Clinical Reaction Time Apparatus ($\chi^2[2] = 19.311, P < 0.001$), Target Capture ($\chi^2[2] = 30.986, P < .001$), Near-Far Quickness ($\chi^2[2] = 41.754, P < 0.001$), Perception Span ($\chi^2[2] = 16.244, P < 0.001$), Eye-Hand Coordination ($\chi^2[2] = 27.096, P < 0.001$), and Go/No Go ($\chi^2[2] = 22.038, P < 0.001$).

We observed a significantly higher linear acceleration in low performers compared to high performers on Target Capture ($F_{1,35} = 9.56; P = 0.004$), Perception Span ($F_{1,35} = 4.22; P = 0.047$), and Go/ No Go ($F_{1,35} = 4.63; P = 0.038$) visual and sensory performance assessments. Additionally, low Go/No Go performers experienced greater rotational acceleration (low performers = 1320.9 rad/s²; 95% CI: 1257.9-1387.1; high performers = 1201.4 rad/s²; 95% CI: 1122.4-1285.9) and HITsp (low performers = 13.8; 95% CI: 13.3-14.2; high performers = 12.9; 95% CI: 12.4-13.4) than high performers (rotational acceleration: $F_{1,35} = 5.29; P = 0.028$; HITsp: $F_{1,35} = 7.84; P = 0.008$). Tables 4.1 and 4.2 include all descriptive and statistical results for all analyses.

Level of Collision Anticipation

We did not observe a significant association between level of anticipation and categorized variable of head impact severity for linear acceleration ($\chi^2[2] = 0.67$, Fisher's Exact $P = 0.161$) or rotational acceleration ($\chi^2[2] = 0.35$, Fisher's Exact $P = 0.174$).

Discussion

The most important finding of our study was that there was a significant association between head impact severity and performance on certain visual and sensory performance assessments in college football players. Specifically, there was a strong association between level of performance on Perception Span, Target Capture, Go/No Go, and Depth Perception and head impact severity, with lower performers sustaining more severe head impacts. These are all complex tests that require a higher level of attentional focus, which may explain for their association to head impact severity in college football. In the future, these tests should be incorporated into preventative visual and sensory training programs to decrease the risk of sustaining injurious head impacts.

Reaction Time

Relationships between CNS Vital Signs and ANAM reaction time measures exist. However, our data did not support our hypothesis that there would be a significant correlation between scores on traditional measures of reaction time and clinical or visual and sensory performance measures. Previous research has shown performance on the Clinical Reaction Time Apparatus was correlated with performance on computerized reaction time tests (Eckner, Kutcher et al. 2010). One reason for the difference in results could be that the previous study used a much larger sample of college football players.

Given our results, it is possible that clinical and visual sensory reaction time measures may provide additional information to clinicians. These findings may also suggest that computerized testing alone may lack the ability to provide a true representative measure of the functional reaction time that is necessary for athletes to participate safely during sports. We submit that further study exploring the utility of clinical and visual sensory reaction time measures in the context of concussion management and developing injury prevention strategies is warranted.

Visual and Sensory Performance

The most important finding of our study was that there was a significant association between head impact severity and performance on certain visual and sensory performance assessments in college football players. Our data supported our hypothesis that a high level of visual and sensory performance is associated with less severe head impacts. Previous research has found that individuals with higher levels of certain aspects of visual and sensory performance, including the characteristics of visual acuity and contrast sensitivity, are able to respond to their environment in a more efficient and appropriate way (Zimmerman, Lust et al. 2011).

We observed a significant association between performance on Perception Span and severity of head impact, with low performers sustaining twice as many severe head impacts than high performers (see Table 4.1 for frequencies). We saw similar associations between performance on Target Capture, Depth Perception, and Go/No Go assessments. This cluster of Nike SPARQ Sensory Station assessments are all unique tests that challenge the subject to quickly and accurately obtain information from a combination of central and peripheral targets through multiple gaze positions.

Additionally, Perception Span, Target Capture, and Go/No Go are all complex tasks that require a higher processing demand. The choice component involved with these assessments requires a higher level of attentional focus to execute at maximal speed with minimal error. The complexity of this cluster of assessments may explain for the strong association to head impact severity. In a sample of college football players, a low level of visual and sensory performance on these assessments could indicate that the athletes are not able to interpret environmental cues, anticipate actions of opponents, and create an appropriate motor response to limit the severity of an impending head impact.

Previous research in visual search behavior and fixation patterns have found that experts tend to have more pertinent search strategies and more frequent fixations of shorter duration early on in the task (Williams, Davids et al. 1994; Martell and Vickers 2004), giving themselves just enough time to extract the appropriate information (Savelsbergh, Van der Kamp et al. 2005). A fixation of longer duration on a particular target, which may be seen in a low performer on these visual and sensory performance tasks, may limit an athlete's ability to anticipate and prepare for an impending impact (Van der Kamp 2011). The findings of our study reveal a need for future research that would study the effectiveness of a visual and sensory training program in decreasing the risk of sustaining injurious head impacts. Specifically, preventative visual and sensory training programs should include the complex attentional tests: Perception Span, Target Capture, Go/No Go, and Depth Perception, which we found to be most predictive of low performers sustaining more severe head impacts.

Visual and Sensory Performance Following Concussion

Two subjects in our study sustained concussions during the data collection period. Injured subject 1 was a linebacker who sustained a concussion during the third quarter of a game while tackling an opponent. This subject was a low performer in six of the nine assessments included in our data analysis (Visual Break, Depth Perception, Near-Far Quickness, Perception Span, Eye Hand Coordination, and Go/No Go). Injured subject 2 was a tight end who sustained a concussion during kick off on a helmet-to-helmet collision. This subject was a low performer in three of the nine assessments (Target Capture, Perception Span, Reaction Time on Nike SPARQ Sensory Station).

Subjects 1 and 2 were both re-evaluated on the Nike SPARQ Sensory Station at 11 days post-injury and 26 days post-injury, respectively. Both subjects were no longer symptomatic and had performed comparable to baseline on computerized neurocognitive and postural testing and were cleared to return to physical activity by their team physician. Subject 1 had the following deficits between his pre and post-injury evaluations: 55% on Contrast Sensitivity, 44% on Depth Perception, 10% on Near-Far Quickness, 5% on Go/No Go, and 13% on Reaction Time. Subject 2 had the following deficits between his pre and post-injury evaluations: 32% on Contrast Sensitivity, 6% on Near-Far Quickness, and 16% on Perception Span.

While the two concussed subjects represent a very small sample size with regards to statistically significant findings, the post-injury evaluation deficits reveal a possibility for additional future research. Using visual and sensory performance assessment tools to determine deficits following a concussion could allow clinicians to have another tool to be incorporated into more sport-relevant return to play guidelines.

Anticipation

Our data did not support our hypothesis that there is an association between level of collision anticipation and head impact severity. Previous research in youth ice hockey players has shown that anticipated collisions resulted in less severe head impacts compared to unanticipated collisions (Mihalik, Blackburn et al. 2010). We had an overall low number of unanticipated collisions, which is consistent with previous research in this area (Ocwieja, 2012). The majority of plays in a football practice or game end in a tackle between two or more players. As a result, athletes are likely expecting to be a part of a collision that may result in a head impact. This may help explain the low number of unanticipated collisions observed in football. Future research should include a larger sample, or possibly combine data from multiple seasons to provide a larger number of unanticipated collisions to be able to better study the association between head impact severity and collision anticipation in college football players.

In addition, while our study assessed visual and sensory performance to attempt to determine an athlete's ability to interpret environmental cues and anticipate the action of opponents, more research is needed to better understand the role of cervical musculature strength and activation in collision anticipation and head impact biomechanics. Cervical muscle strengthening could decrease the risk of concussion based on the principal that tensing the cervical musculature increases the effective movable mass of the head, neck, and torso; thus increasing the ability to overcome the force of a possibly injurious head impact (Mihalik, 2011). Previous research in this area is limited by using isometric "break tests" to measure cervical muscle strength that may not relate to the activation of cervical musculature that occurs while participating in sports (Mihalik, Guskiewicz et al.

2011). Future research needs to identify a more sport-appropriate way to measure cervical muscle activation to better understand the factors that affect an athlete's ability to create the appropriate motor response following an anticipated or unanticipated collision.

Conclusion

The findings of our study reveal a link between level of visual and sensory performance and head impact biomechanics in college football players. While the exact relationship between level of anticipation and head impact severity in this population is not entirely clear, it is likely that an athlete's visual and sensory performance may be related to their ability to anticipate and react to impending head impacts on the field. Specifically, there was a strong association between level of performance on Perception Span, Target Capture, Go/No Go, and Depth Perception and head impact severity, with lower performers sustaining more severe head impacts. Future research should include these tests to identify at-risk athletes and create preventative training interventions to hopefully decrease their overall risk of injurious head impacts.

Table 4.1. Frequency (percentage) of recorded impacts sustained by high and low performers of visual and sensory assessments by an ordinal level of head impact severity based on linear and rotational accelerations.

	Head Impact Severity- Linear Acceleration Frequency (%)			Head Impact Severity-Rotational Acceleration Frequency (%)		
	Mild <66g	Moderate 66-106g	Severe >106g	Mild <4600g	Moderate 4600-7900g	Severe >7900g
Visual Break						
High Performer	9275(47.66)	$(\chi^2[2] = 2.909, P = 0.234)$ 314 (1.61)	58 (0.30)	9413 (48.37)	$(\chi^2[2] = 2.907, P = 0.234)$ 199 (1.02)	35 (0.18)
Low Performer	9473 (48.68)	295 (1.52)	45 (0.23)	9546 (49.05)	236 (1.21)	31 (0.16)
Depth Perception						
High Performer	8983 (46.16)	$(\chi^2[2] = 11.852, P = 0.003^*)$ 249 (1.28)	47 (0.24)	9065 (46.58)	$(\chi^2[2] = 5.316, P = 0.070)$ 184 (0.95)	30 (0.15)
Low Performer	9765 (50.18)	360 (1.85)	56 (0.29)	9894 (50.84)	251 (1.29)	36 (0.18)
Near-Far Quickness						
High Performer	9274 (47.66)	$(\chi^2[2] = 10.042, P = 0.007^*)$ 316 (1.62)	66 (0.34)	9337(47.98)	$(\chi^2[2] = 41.754, P < .001^*)$ 281(1.44)	38 (0.20)
Low Performer	9474 (48.68)	293 (1.51)	37 (0.19)	9622 (49.45)	154 (0.79)	28 (0.14)
Target Capture						
High Performer	10403 (53.46)	$(\chi^2[2] = 44.572, P < .001^*)$ 263 (1.35)	42 (0.22)	10493 (53.92)	$(\chi^2[2] = 30.986, P < .001^*)$ 184 (0.95)	31 (0.16)
Low Performer	8345 (42.88)	346 (1.78)	61 (0.31)	8466 (43.50)	251 (1.29)	35 (0.18)
Perception Span						
High Performer	8496 (43.66)	$(\chi^2[2] = 36.317, P < .001^*)$ 211 (1.08)	31 (0.16)	8557 (43.97)	$(\chi^2[2] = 16.244, P < .001^*)$ 159 (0.82)	22 (0.11)
Low Performer	10252 (52.68)	398 (2.05)	72 (0.37)	10402 (53.45)	276 (1.42)	44 (0.23)
Eye-Hand Coordination						
High Performer	9814 (50.43)	$(\chi^2[2] = 2.121, P = 0.346)$ 305 (1.57)	49 (0.25)	9957 (51.17)	$(\chi^2[2] = 27.096, P < .001^*)$ 174 (0.89)	37 (0.19)
Low Performer	8934 (45.91)	304 (1.56)	54 (0.28)	9002 (46.26)	261 (1.34)	29 (0.15)
Go/No Go						
High Performer	9875(50.75)	$(\chi^2[2] = 12.092, P = 0.002^*)$ 289(1.49)	42(0.22)	9986(51.32)	$(\chi^2[2] = 22.038, P < .001^*)$ 181(0.93)	39(0.20)
Low Performer	8873(45.60)	320(1.64)	61(0.31)	8973(46.11)	254(1.31)	27(0.14)
Reaction Time (SPARQ)						
High Performer	8506 (43.71)	$(\chi^2[2] = 21.166, P < .001^*)$ 318 (1.63)	63 (0.32)	8603 (44.21)	$(\chi^2[2] = 25.187, P < .001^*)$ 246 (1.26)	38 (0.20)
Low Performer	10242 (52.63)	291 (1.50)	40 (0.21)	10356 (53.22)	189 (0.97)	28 (0.14)
Reaction Time (Clinical)						
High Performer	7918 (40.69)	$(\chi^2[2] = 0.311, P = 0.856)$ 254 (1.31)	41 (0.21)	8041 (41.32)	$(\chi^2[2] = 19.311, P < .001^*)$ 140 (0.72)	32 (0.16)
Low Performer	10830 (55.65)	355 (1.82)	62 (0.32)	10918 (56.10)	295 (1.52)	34 (0.17)

¹ * Significant *P* values ($p > 0.05$)

Table 4.2. Mean resultant linear acceleration, rotational acceleration, and HITsp of head impacts sustained by high and low performers of visual and sensory performance assessments.

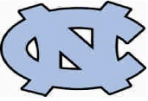
	Linear acceleration (g)			Rotational acceleration (rad/s ²)			HITsp		
	Mean	95% CI L U	<i>P</i> ^b	Mean	95% CI L U	<i>P</i> ^b	Mean	95% CI L U	<i>P</i> ^b
<i>Visual Break</i>									
High Performer	22.4	21.3 23.5	(Ref)	1252.2	1178.7 1330.2	(Ref)	13.3	12.7 13.8	(Ref)
Low Performer	22.0	21.3 22.7	0.538	1254.7	1170.0 1345.5	0.965	13.3	12.8 13.7	0.985
<i>Depth Perception</i>									
High Performer	21.6	20.8 22.5	(Ref)	1215.7	1127.5 1310.7	(Ref)	13.0	12.5 13.5	(Ref)
Low Performer	22.8	21.9 23.7	0.065	1290.8	1227.2 1357.8	0.188	13.5	13.0 14.0	0.161
<i>Near-Far Quickness</i>									
High Performer	21.9	21.0 22.9	(Ref)	1250.3	1150.1 1359.3	(Ref)	13.1	12.6 13.8	(Ref)
Low Performer	22.5	21.6 23.3	0.401	1256.3	1201.4 1313.6	0.920	13.4	13.0 13.8	0.533
<i>Target Capture</i>									
High Performer	21.3	20.5 22.2	(Ref)	1202.6	1121.7 1289.3	(Ref)	13.0	12.6 13.6	(Ref)
Low Performer	23.1	22.4 23.8	0.004*	1305.9	1236.2 1379.5	0.068	13.5	13.0 14.0	0.213
<i>Perception Span</i>									
High Performer	21.5	20.7 22.4	(Ref)	1233.4	1152.7 1319.9	(Ref)	13.0	12.5 13.5	(Ref)
Low Performer	22.8	21.9 23.7	0.047*	1270.1	1192.8 1352.5	0.524	13.5	13.0 14.0	0.206
<i>Eye-Hand Coordination</i>									
High Performer	21.9	21.1 22.7	(Ref)	1212.2	1146.0 1282.2	(Ref)	13.1	12.7 13.6	(Ref)
Low Performer	22.5	21.5 23.6	0.307	1300.4	1211.8 1395.5	0.123	13.4	12.9 13.9	0.488
<i>Go/No Go</i>									
High Performer	21.6	20.8 22.5	(Ref)	1201.4	1122.4 1285.9	(Ref)	12.9	12.4 13.4	(Ref)
Low Performer	22.9	22.1 23.8	0.038*	1320.9	1257.9 1387.1	0.028*	13.8	13.3 14.2	0.008*
<i>Reaction Time (SPARQ)</i>									
High Performer	22.6	21.9 23.3	(Ref)	1287.9	1218.6 1361.0	(Ref)	13.5	13.0 13.9	(Ref)
Low Performer	21.7	20.7 22.8	0.175	1217.9	1132.1 1310.2	0.224	13.0	12.5 13.6	0.231
<i>Reaction Time (Clinical)</i>									
High Performer	22.6	21.7 23.5	(Ref)	1247.7	1169.8 1330.7	(Ref)	13.3	12.8 13.9	(Ref)
Low Performer	21.8	20.9 22.7	0.223	1259.0	1178.3 1345.1	0.845	13.2	12.8 13.7	0.793

^a *P* values are relative to the reference category used by the random intercepts general mixed linear model analyses


^b Denotes the reference (Ref) category


APPENDIX A

The Player-to-Player Collision Type Evaluation Form



Player to Player Collision Type Evaluation Form




 50848

Impact

0									
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Quarter

00			
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Game Clock

--	--	--	--	--	--

Rater:

00			
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C1. Play Type

☐ Punt (0)
☐ Punt Return (1)
☐ Kickoff (2)
☐ Kickoff Return (3)
☐ Offense Pass (4)
☐ Offense Rush (5)

☐ Defense Pass (6)
☐ Defense Rush (7)
☐ Field Goal (8)
☐ Field Goal Block (9)
☐ Extra Point (10)
☐ Extra Point Block (11)

C2. Closing Distance Type

☐ Long Distance (0)
☐ Short Distance (1)
☐ Unknown (2)

C3. What stance did the opponent begin in

☐ 2pt (0)
☐ 3pt (1)
☐ 4pt (2)

☐ Unknown (3)
☐ N/A (4)

C4. What stance did UNC begin in

☐ 2pt (0)
☐ 3pt (1)

☐ 4pt (2)
☐ Unknown (3)

C5. Player involvement in body collision

☐ Striking player (0)
☐ No (0)

☐ Player struck (1)
☐ Yes (1)

☐ Unknown (2)

C6. Player looking ahead in direction of movement

☐ No (0)

☐ Yes (1)

☐ Unknown (2)

C7. Player appears to be looking in direction of impending body collision

☐ No (0)

☐ Yes (1)

☐ Unknown (2)

C8. Was the opponent stationary

☐ No (0)
☐ Yes (1)

☐ Unknown (2)
☐ N/A (3)

C9. Was the UNC player stationary

☐ No (0)
☐ Yes (1)

☐ Unknown (2)

C10. Did the player have possession of the ball

☐ No (0)
☐ Yes (1)

☐ Unknown (2)

C11. Was the player receiving/passing the ball at time of collision? (hand-off, pitch, pass, catch)

☐ No (0)
☐ Yes (1)

☐ Unknown (2)

C12. Was the player snapping the ball (center)

☐ No (0)
☐ Yes (1)

☐ N/A (2)

C13. Infraction type associated with collision

☐ Legal (clean) collision (0)
☐ Spearing (1)
☐ Head to head contact (2)
☐ Facemask/cowbow collar (3)
☐ Unknown (4)
☐ Other (5)

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C14. Overall impression of body collision

☐ Anticipated (0)
☐ Unanticipated (1)
☐ Unknown (2)

Additional Comments:

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