EFFECTS OF HEAD IMPACT BIOMECHANICS ON VISUAL-MOTOR PERFORMANCE OVER THE COURSE OF A COLLEGE FOOTBALL SEASON

Philippe Gagnon-Joseph

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Approved by:

Jason P. Mihalik

Johna K. Register-Mihalik

Catherine B. Ford

ABSTRACT

Philippe Gagnon-Joseph: Effects of Head Impact Biomechanics on Visual-Motor Performance Over the Course of a College Football Season
(Under the direction of Jason P. Mihalik)

Sports-related concussions have been shown to cause visual impairments while there is uncertainty regarding the neural effects of sub-concussive head impacts. Given the complexity of visual-motor sensory integration, it seems possible that if subconcussive impacts result in a neural defect, this deficit could manifest itself as a decrement in visual performance. The purpose of this study was to examine the relationship between visual-motor performance and head impact biomechanics in Division I College football players. We found that players with poorer pre-season visual-motor performance demonstrated more severe head impact biomechanics. We also found that high severity subconcussive head impacts can have negative effects on visual-motor performance.

TABLE OF CONTENTS

LIST OF TABLES

CHAPTER I: INTRODUCTION

With an estimated 1.6 to 3.8 million cases per year, sport-related traumatic brain injury (TBI) is a significant concern for athletes, families, coaches, and medical staff alike.[1] A concussion is a mild form of TBI with transient impairment of neural function that results in decrements in cognition, balance, and vision.[2] High school and college American football has one of the highest concussion incidence rates compared to sports such as soccer, basketball, and others. Therefore, reducing concussion risk, specifically by decreasing the exposure to head impacts, in American football is a significant goal in sports medicine.[3]

Concussions are caused by a combination of linear and rotational forces causing sudden head acceleration/deceleration.[4] Because the brain is enclosed in the skull, limiting its ability to dissipate force, a rapid deceleration can cause large forces to act on the brain, which may cause axonal shearing, metabolic disruptions, and consequent impairments in neural function.[4] Research in the area of head impact biomechanics has yet to find an impact magnitude threshold above which a concussion will occur.[2] However, this literature has revealed a correlation between concussion risk and impact magnitude; the greater the impact, the higher the concussion risk.[5] Thus, reducing high magnitude impacts is believed to lower the overall concussion risk.[5]

Improving an athlete's ability to anticipate an impact may reduce the athlete's exposure to high magnitude impacts, and thus, lower their concussion risk. Anticipating an incoming impact may decrease the overall impact magnitude by activating neck musculature and increasing the head's deceleration time during an impact.[4] Corroborating this hypothesis, anticipated impacts result in less severe head impacts in hockey; however, research conducted in the Division 1 football setting is unclear on the matter.[6,7] It has been hypothesized that impact anticipation involves integration of visual cues and an appropriate motor response.[6,8,] In relation to this, Harpham et al. (2014) observed an association between head impact severity and performance on certain visual-motor tests including perception span, target capture, go/no go, and depth perception. Football players who demonstrated poorer pre-season performance on these functional vision tests sustained more severe head impacts over the course of the following season.[6]

The goal of this study is to build on the results found by Harpham et al. (2014) by doing both pre and post season visual-motor testing. This will allow us to determine whether or not exposure to head impacts over the course of the season will predict pre- to post-season changes in visual-motor processes relative to pre-season measures. There is growing science supporting the theory that visual dysfunction is a more pervasive concussion symptom than once believed.[9] It is possible that exposure to head impacts over the course of a season may cause decreased performance on vision and sensory performance measures. Confirming an association between the two may offer an alternative way of measuring risk for the development of underlying neurophysiological changes purported to accompany late-life and long-term neurological declines associated with football participation.[10]

Specific Aims & Hypotheses

Specific Aim 1. To test the hypothesis that Division I college football players with poorer preseason visual and sensory performance will demonstrate more severe head impact biomechanics (linear and rotational acceleration) than those with better preseason visual and sensory performance (as measured by the Senaptec Sensory Station).

Hypothesis 1: Head impact severity (as measured by mean linear and rotational accelerations) will be greater in football players with poor pre-season visual and sensory performance compared to those with good visual and sensory performance.

Specific Aim 2. To test the hypothesis that preseason-to-postseason changes in visual and sensory performance are predicted by head impact biomechanic severity in college football players.

Hypothesis 2: Severity of head impact biomechanics in college football players over the course of a season will predict change in visual and sensory performance on depth perception, target capture (dynamic visual acuity), perception span, and go/no-go tests as measured on the Senaptec Sensory Station; where an increased head impact severity would predict a decline in visual and sensory performance.

Clinical Significance

Visual-motor processing is an integral part of athletic performance. Disrupting that processing due to concussive episodes or repeated subconcussive head impacts has the potential to increase susceptibility to initial or recurrent injury.[11]

The Integrated Recovery Model of concussion put forward by the NCAA-DoD CARE Consortium Advanced Research Core, and supporting research, suggests that prior to full recovery from concussion, there is a post-acute phase where there can be full clinical recovery, but physiological dysfunction still persists.[12,13,14] It is at this point that many football athletes of all ages and performance levels are returned to play due to the resolution of clinical symptoms. Current guidelines state that concussion diagnosis is based on the clinical domains of somatic/cognitive/emotional symptoms, physical signs, behavioral changes, cognitive impairment, and sleep disturbance.[15] Return to play criteria following concussions dictate an absence of those previously stated signs and symptoms, which may not align with a full physiological recovery. The discovery of these subacute physiological dysfunctions seen in concussion and repetitive head trauma in sports is relatively new and underexplored. As such, there are a limited number of practical tests or tools that have been developed to assess them. Given that up to 90% of individuals with a traumatic brain injury (TBI) report vision disturbances, and approximately half of the cranial nerves in the human brain are involved in vision, we eventually hope to use visual-motor performance as an assessment tool for concussions (which is a mild TBI).[16,17] Assessment tools for repetitive head trauma have already been developed, and allow for the collection of head impact biomechanics in sports such as football.[18]

The 2 between individuals who suffered concussions and individuals who suffered multiple head impacts with no concussive episode seems to suggest that visual-motor performance analysis might be important for all athletes who are exposed to head impacts.[13,19] A decreased ability to integrate visual information could lead to a decrease in anticipation and delayed motor response, which have been shown to correlate with an increased severity of head impacts.[8] The overarching goal of this study is to determine if increased head impact severity and frequency leads to a decreased ability to integrate and act on visual sensory information. Should a relationship between the two be found, not only could this allow for pre-season screening for high risk athletes, but also an athlete with a marked in-season decrease in visual-motor performance from his/her baseline could be flagged as high risk for injury, and could be appropriately followed by the medical staff. We wish to use the Senaptec Sensory Station and Head impact telemetry (HIT) System to evaluate the relationship between head impact exposure and visual-motor performance in Division 1 Football athletes.

Some research has already shown benefits of vision training, and finding a relationship between head impact exposure and visual-motor performance in this study would strengthen a case for more research to be performed on vision training, specifically within Division 1 football.[20,21] Having a tool to identify and correct a deficit in visual-motor processing would allow us to protect vulnerable athletes, rehabilitate them, and eventually improve sports performance.

CHAPTER II: LITERATURE REVIEW

"Concussion is a brain injury and is defined as a complex pathophysiological process affecting the brain, induced by biomechanical forces."[15]

Epidemiology

As our understanding of concussions progresses so does our awareness of its incidence in sports. Non-fatal traumatic brain injuries saw a 62% increase between 2001 and 2009, which could be due to an increase in symptom recognition and lay person education.[22] An estimated 3.8 million reported and unreported sport/recreation-related concussions occur each year in the USA. [1,22] At the collegiate level, concussions represent 6.2% of total injuries reported to the NCAA.[23] Football, the focus of this study, had the greatest number of concussions with 603, representing 36.1% of reported concussions (5% of which were recurrent).[23] This high number of concussions is mainly due to the large number of football players, as wrestling and ice hockey both had higher rates of concussion,[23] but it could also be attributed to the physical and aggressive nature of football which involves repeated intentional and unintentional collisions.[24]

Pathophysiology of concussion and subconcussive impacts, and how they affect visual-motor processes

Concussions as we understand them are a result of acceleration and deceleration forces that cause neuronal shearing (tearing or stretching),[22,4] as well as a neurometabolic cascade that can have detrimental effects on multiple functions of the brain.[25] This means that concussions are both structural and functional injuries wherein a mechanical force causes structural changes to neurons that affect their function.

Trauma leads to alterations in the brain affecting ionic balance, cerebral blood flow, and glucose metabolism.[25] Brain trauma causes increased binding of excitatory neurotransmitters which leads to increased depolarization in neurons.[25] This continuous depolarization leads to an efflux of potassium and an influx of calcium.[25] Due to this, the sodium-potassium pump has to work harder to restore balance, thus requiring more adenosine triphosphate for the process. This increase in energy demand leads to a large increase in glycolysis metabolism. The surge in cerebral glucose metabolism is followed by a decrease in glucose metabolism that can last for up to 2 to 4 weeks.[12,25] Coupled with trauma-induced decrease in cerebral blood flow, this puts the brain in a vulnerable position as its cells are requiring more glucose than can be delivered.[26] Brain cells find themselves in a glucose-depleted state which could mean that the brain is more vulnerable to re-injury because an increase in glucose need cannot be met.[12,25] While these alterations themselves are not always debilitating or life threatening, they put the person at an increased risk for re-injury of the brain.[27,25] In order to make appropriate return to play decisions, we need to understand the neurometabolic cascade that occurs post-concussion, and its timeline.

Common signs and symptoms of a concussion include headache, dizziness, nausea, retrograde amnesia, anterograde amnesia, disorientation, motor control impairments, and neurocognitive impairments.[4,22,24,25] The plethora of signs and symptoms that can occur when a person is concussed is due to the diffuse nature of the injury.[22,25] Although these forces will cause structural damage and metabolic changes, these changes are transient, as are the accompanying signs and symptoms.[24,28] Given the diffuse nature of concussive injuries, visual function is often impaired following a concussion.[29] The presence of visual deficits makes visual information integration difficult, which in turn can affect visual-motor processing.[11]

Collegiate football players who are exposed to repetitive head impacts can display long-term changes in cerebral white matter, despite a lack of cognitive or balance deficits associated with concussions.[13] Also, upon autopsy, neurological changes can sometimes be observed in brains of elite football players with no history of concussion; changes which are similar to what is seen in football players who suffered from chronic traumatic encephalopathy following multiple concussions.[10] This hints to the potential for long term neurological changes due to sub concussive impacts, which may mirror changes that follow repeated concussions.[10]

Some collegiate football players do not display any clinically relevant impairments following exposure to subconcussive head impacts over the course of a season, despite previously mentioned long term neurological changes that can sometimes be observed.[13,30] Also, a relationship between accumulated head impacts over the course of a collegiate football season and changes in neurologic function is not always evident.[30] More research is needed to determine what clinically relevant effects, if any, repeated exposure to subconcussive impacts have on athletes.[10,13,30] This study will contribute to this literature by testing visual-motor function pre and post season with the Senaptec Sensory Station, an assessment tool which may be sensitive enough to detect changes in visual-motor processing due to subconcussive impacts.

Head Impact Biomechanics in Football

Concussions are thought to be caused by linear and rotational head accelerations via direct or inertial (indirect) forces. When trying to understand the effects of different types of collisions on the brain, Newton's second law can be used.[4] The formula for this law is: $F = mv^2/2s$, where F is force, m is mass, v is velocity at impact, and s is distance over which the head will decelerate. From the formula, we know that increasing collision velocity or decreasing distance of deceleration will increase the force acting on the brain.

In recent years, concussion research has been focused on trying to determine the effects of impact location (on the helmet) and magnitude on clinical concussion outcomes, as well as the impact threshold required to cause a concussion.[31] A previous theory regarding concussion was that the higher the magnitude of impact that was sustained, the worse the clinical outcome will be, but the research does not support this.[31] Furthermore, the wide range of impact location and impact magnitudes seen in the mechanism of injury of concussed individuals have made it difficult to confirm the previously proposed impact thresholds for concussion of 70-75g.[2,31] This may be due to inherent differences in anticipation, muscle strength, and differences in vulnerability of brain tissue from one person to another.[2] Despite the lack of a clear impact magnitude threshold for concussion, recent literature has defined a high magnitude impact as producing a linear acceleration above 80-106g (depending on the article).[6,30,32,33]

Although a force threshold is unclear, we do know that rotational forces are more likely to result in a loss of consciousness. The midbrain and upper brainstem are responsible for alertness and responsiveness, therefore rotation of the cerebrum about the brainstem produces neuronal shearing that could alter those functions.[2] It has also been shown that players are more likely to sustain larger magnitude head impacts to the top of the head than either the front, back, or sides.[31,33] Guskiewicz et al. (2007) observed that impacts to the top of the helmet may be more likely to cause a concussion, and show larger postural control deficits than impacts to other locations on the helmet.[31] Also, Broglio et al. (2010), hypothesized that the higher rotational acceleration observed by an impact to the side (temporal region) of the helmet, may increase concussion risk.[32]

There are multiple factors outside of head impact location and direction that influence the risk of sustaining a concussion while playing collegiate football including player position, setting (game vs. practice), and play type.[23,27,34,35] Most studies have reported that offensive linemen, running backs, linebackers, and defensive backs are at the greatest risk of sustaining a concussion.[27,34,35] While a majority of concussions in collegiate football occur during practice (51.5% to 56.6%), the rates of injury are higher during competition.[23,27] This can be explained by the increased intensity and speed of games in comparison to practices.[27] In general, concussions in football commonly occur during contact with another person, specifically while blocking (14.8% to 20.4%), and tackling (19.9% to 21.4%).[23,27] Running plays (inside runs specifically) involve multiple instances of blocking and tackling in a small area, and have been shown to be the type of plays during which the most concussions occur.[27,34,35]

Given that this study's main interest is the result of head impacts over a long period of time, it is interesting to note that collegiate football players can be exposed to well over 1000 head impacts in a single season, with an average of 4.8 to 6.6 impacts per practice, and 12.1 to 16.3 impacts per game.[36] Much like the risk of sustaining a concussion, the number of impacts players experience is not just related to session type, but also to player position. Linemen and linebackers are exposed to the largest number of head impacts in both practices and games, which may help explain why these groups are also reported to have the highest incidences of concussion.[32] Within the linemen group, it has been shown that offensive linemen sustain larger magnitude head impacts more often than defensive linemen, which may explain why offensive linemen sustain more concussions.[27,33–35] Furthermore, running backs are more likely than any other position group to record impacts over 80g of force, which may explain why running backs are at a high risk for concussions. [27,34,35] These differences in risk of concussion based on magnitude and number of head impacts could also be relevant to cases involving repeated sub-concussive impacts. Increased exposure rates could cause more long-term neurological damage, and could have clinical effects.[37] This may be difficult to determine due to the wide range in number and magnitudes of impact observed in collegiate football.

Guskiewicz et al. (2007) analyzed over 100,000 head impacts from 88 collegiate football players over three years.[31] During that time there were 13 concussions, providing insight into the head impact biomechanics of concussions. Within the concussed group, the average number of sustained impacts was 27.7, but the range was from 1 to 121, showing that the average of these data points doesn't provide much information regarding concussion prediction via average number of sustained impacts in a season.[31] Similarly, the average magnitude within this group was 102.8g, with a range from 60.51g to 168.75g; 60.51g being significantly lower than most proposed concussion thresholds.[2] Once again, the wide range of collected impact magnitude data doesn't provide enough information for concussion prediction based on impact magnitude, hence the difficulty with setting a magnitude threshold for concussions. [6,30,32,33] This lack of a magnitude threshold for concussions also creates difficulty when studying sub-concussive impact. Any impact, no matter how big or small, can potentially be sub-concussive. Grouping a 20g impact and a 200g impact into the same "subconcussive" category can be problematic given that we do not understand their differential effect, if any, on long term neurological outcomes.

This study is ultimately interested in predicting subacute neurological deficits. In particularly, the effects of cumulative head impacts on the sensory-motor system over time. Gysland et al. (2012) studied the relationship between repeated subconcussive head impacts over the course of a collegiate football season and neurologic function in forty-eight football players. These athletes averaged 12.0 ± 11.1 impacts above the a priori 90 g "high magnitude" impact threshold.[30] This shows that every season the average collegiate football player may sustain multiple head impacts of high enough magnitude to cause a concussion, but do not report clinically relevant symptoms. Also, head impact biomechanical metrics were unable to explain pre to post season changes in neurocognitive performance, yet a higher number of severe head impacts, impacts to the top of the head, and number of participation years were significant predictors of an increase in reported symptoms on the Graded Symptom Checklist from pre to post season.[30]

Furthermore, Eckner et al. (2011), who recorded over 100,000 impacts in 95 high school football players over four seasons, found no correlation between cumulative subconcussive impacts and concussion incidence.[38] A limitation in this study is that they were defining cumulative impacts as the three non-concussive impacts with the largest

HITsp value, not hundreds of impacts over time. The HITsp is a composite score which includes linear and rotational acceleration, as well as other factors; and the case of the data points recorded in this study, a larger HITsp value also meant a larger linear and rotational acceleration.[38] We will not be using the HITsp in the analysis of our study due to its limited ability to bring clinically relevant information to the table that would not be captured by metrics such as magnitude of linear and rotational acceleration, and impact frequency and location.

Validation of the Head Impact Telemetry System

The Head Impact Telemetry (HIT) System (Simbex, Lebanon, NH; Riddell, Rosemont, IL) was developed in 2003.[39] It uses six accelerometers mounted in well fitted helmets and special predictive algorithms to compute head impact kinematics and calculate linear and rotational acceleration, and has a minimum threshold of 15g.[18,32,39] Overall, literature has shown that the HIT System has validity in the lab and on the football field, but that validity can differ depending on impact site and proper helmet fitting.[40] Despite this, the HIT System is still able to detect 96.1% of impacts.[18] However, there are still concerns about the accuracy of the system. Comparisons between the Hybrid III, which is considered the gold standard in measurements of head acceleration, and the HIT System, have shown a lack of validity of the HIT System, especially for impacts occurring to the facemask.[41] The HIT System can make 12.3-22.8% errors in linear acceleration calculation, and 30-110.7% errors in rotational acceleration, depending on the area of impact.[41] These inaccuracies in HIT System calculations, especially in rotational acceleration, need to be taken into consideration when drawing conclusions from these data. Combined with the wide range of impact magnitudes and locations at which concussions have been observed, it is difficult to use acceleration calculations from the HIT System to predict or diagnose a concussion; meaning the data should be interpreted with care.[31]

Some research has shown that high school and college football players sustain greater amounts and higher severity impacts on the day they are diagnosed with a concussion.[40] This would mean that although the existence of a specific impact threshold is unknown, it does seem that a higher frequency of severe head impacts, as determined by HIT System recordings, increases the chances of sustaining a concussion. Although we cannot necessarily use the HIT System as a predictive or diagnostic tool, it can provide us with valuable information about the events surrounding an injury, as well as a given athlete's risk of sustaining a concussion, which is why we are using it in this study.

Collecting head impact data over the course of a season will allow us to obtain a global view of the impacts each player sustains. Using these data, we will calculate averages of magnitude of linear acceleration, and rotational acceleration for all participants in the football group.[6]

Vision

A high level of visual processing ability is key to elite performance in all sports. The ability to anticipate an incoming impact correlates with smaller head impact magnitudes in youth hockey players.[8] Given that there are contradictory findings in research conducted in a football setting, more work is needed to determine if anticipation has an effect on magnitude of head impact in collegiate football.[42] The visual- motor processes allowing for anticipation of an impending impact, an appropriate reaction, and eventually a reduced impact magnitude, could be the same in both sports. By measuring post-season visual-motor performance, and in-season head impact biomechanics, this study aims to determine if frequency and magnitude of head impacts over the course of a season in turn have an effect on the visual-motor processes of collegiate division I football players.

High performance on visual-motor tasks depends on the two main processing systems involved in vision: ambient (peripheral) visual processing and focal (central) visual processing.[43] These processes can be measured by looking at visual fixation duration and oculomotor saccade amplitude.[43] Visual fixation duration is the amount of time the eye holds the image of an object on the fovea.[44] Oculomotor saccades are rapid eye movements that bring a given object onto the fovea.[44] Ambient visual processing usually occurs when the eye is initially presented with an image and involves short fixations of the eye and large saccade amplitudes. The result is an accumulation of rapid, low frequency information from peripheral vision that gives the brain spatial awareness.[45] An example of this would be the initial ocular reaction to a Landolt ring appearing on the screen during a dynamic visual acuity test (see next section for explanation).

Focal visual processing usually occurs when peripheral visual information has been gathered, and there is a desire to shift attention towards specific visual details. Information on these details can be gathered via long fixation times and small saccade amplitudes.[45] The result is an accumulation of high frequency, central information.[45] The idea that the eyes alternate between ambient and focal visual patterns has long since been established for situations where the eyes are observing a static image.[43] But only recently has a study determined that the same processes occur when the eye is presented with a dynamic, “natural” image.[45] An example of this transition from ambient to focal visual patterns would be using focal visual processing to determine which direction the Landolt ring is facing, after using ambient visual processing to localize the Landolt ring itself on the screen during a dynamic visual acuity test.

In addition to fixations and saccades, the eye uses smooth pursuits in order to keep a moving target within the fovea; vergence to follow objects as they move closer (convergence) or farther (divergence) from oneself; and accommodation to change focus from one object to the next.[46] These processes are the basis of vision, and are therefore part of the underlying mechanisms necessary for high performance in sports. For example, a receiver catching a ball would require a mix of fixations and saccades to localize and identify a football, then smooth pursuits and vergence to keep track of the incoming ball. As described in the next section, the Senaptec Sensory Station tests all these different components of visual-motor abilities in different ways throughout the test.

Studies have shown that up to 90% of individuals with TBI report vision disturbances, and approximately half of the cranial nerves in the human brain are involved in vision.[16,17] Given the potential similarities in long term neurological changes seen in athletes who sustained concussions and athletes who sustained a high number of subconcussive head impacts, it is important to determine if athletes who sustain a large number of head impacts but present with no clinical deficiencies have visual dysfunctions. The Senaptec Sensory Station may be able to provide us with this information, which could become clinically relevant in the context of injury prevention, long term athlete health, and athletic performance.

Validation of Senaptec Sensory Station

Visual-motor processing is an inherently important aspect of sports. Athletes rely on different visual cues to react and perform in their sports. The Senaptec Sensory Station was built to help assess these visual-motor abilities by re-creating visual scenarios that require oculomotor fixations, saccades, pursuit, vergence, and accommodation similar to what is required in every day vision. Research has shown that concussions often disrupt these basic oculomotor functions, and in this study our aim is to determine if subconcussive head impacts can have a similar negative effect.[46]

The Senaptec Sensory Station's precursor is the Nike SPARQ Sensory Station, which is no longer in operation but measured similar components as the Senaptec Sensory Station. Both units use screens and tablets to measure static visual acuity, contrast sensitivity, depth perception (stereopsis), near-far quickness, dynamic visual acuity, perception span, eye-hand coordination, go/no-go, and hand response time.[47,48] Although both stations test the same visual constructs, there is no literature to date establishing the Senaptec Sensory Station's reliability.

Static visual acuity (SVA) is a measure of "the minimum detectable spatial resolution for a non-moving object".[47,48] Wang et al. (2015) showed a significant correlation between SVA, as measured by the Snellen Eye Chart and the Nike SPARQ Sensory Station, thus validating the computer test. Dynamic visual acuity (DVA) is the ability to resolve "a brief peripherally presented target".[47] For example, in football receivers must detect an incoming high-velocity football through his peripheral vision, and distinguish it from another object, such as a players arm. High performance on a DVA test may therefore be crucial to success in football. Contrast sensitivity is the assessment of the minimum amount of contrast that can be used to distinguish light from dark, which is important in any outdoor sport given the unpredictability of lighting.[47,48] Depth perception is the minimum distance one can use to distinguish differences in depth, and is crucial to all sports, especially ones that revolve around throwing and catching of balls with moving targets at different depths.[47,48]

Psychomotor tasks include near-far quickness, perception span, eye-hand coordination, go/no-go, and hand response time.[47] Near-far quickness is the assessment of the speed and accuracy with which one can visually accommodate from one target to another.[47,48] Perception span assesses one's ability to recreate patterns of increasing complexity, which is a measure of visual memory.[47,48] Go/no-go tests one's ability to respond on command and inhibiting that response on command.[47,48] Eye-hand coordination is the ability to touch a designated structure quickly, repetitively, and accurately when it is moved randomly at each touch.[47,48] Hand response time is the ability to move one's hand from point A to point B as quickly and as accurately as possible.[47] Unlike the Nike SPARQ station, the Senaptec Sensory Station has a multiple object tracking task, which involves tracking objects through space amidst distractions. This task would be important for all positions in football given that there are 22 players on the field at any given moment who all need to make decisions based on movement patterns. Much like the previous section of tests, the psychomotor tests are directly related to necessary visual-motor function for the game of football. Also, a link has been found between head impact severity and performance on the following tests: perception span, target capture, go/no-go, and depth perception.[6] Lower performers on these visual-motor tests sustained more severe head impacts, and as such, will be of special interest in this study.[6]

The Nike Sensory Station's assessment tools have been shown to have repeatability and minimal learning effect over time.[48] As previously discussed, the Senaptec Sensory Station has not been validated, and although test designs are comparable to that of the Nike SPARQ Sensory Station, more research needs to be conducted in order to ascertain its validity. We hope to add to growing research and provide new validation to the Senaptec Sensory Station by replicating the study by Harpham et al. (2014).

Rationale

Anticipated collisions have been shown to result in less severe head impacts than unanticipated collisions in youth hockey.[8] Although hockey and football are different sports, a case could be made that given similarities in physiology across people, the same should be true for football. In the limited existing research on anticipation in football, there is no correlation between anticipation and head impact magnitudes, but the lack of large scale studies means these results are not conclusive.[7] Also, better visual-motor performance has been shown to correlate with decreased exposure to high magnitude impacts.[6] Athletes with better visual and sensory performance may be able to do a better job of anticipating impact than those with worse visual and sensory performance, leading to less severe head impacts.[6] The ability to anticipate an impact is thought to decrease the severity of an impact by allowing the time to contract cervical neck musculature, thus increasing the deceleration time of the head.[4] In order to strengthen our understanding of the correlation between head impact biomechanics and visual-motor processing, we need to know what effect head impact biomechanics have on those processes. Therefore, the goal of this study is to gain information on the effect of head impact biomechanics on visual and sensory performance, as assessed by the Senaptec Sensory Station, over the course of a season of Division 1 football.

CHAPTER III: METHODS

Study Design and Participants

This study was a prospective, observational study within a group of College Division I football players. Given the use of continuous variables in this study, and the lack of consensus regarding a cutpoint for identifying individuals with low and high impact exposure, we decided not to dichotomize our results, which could run the risk of decreasing statistical power of our results.[49]

We recruited 35 male college Division I football players (age = 20.6 ± 1.3 years; height = 188.0 ± 7.1 cm; mass = 109.4 ± 44.3 kg) based on the following inclusion criteria: 1) were part of the 2017 University of North Carolina at Chapel Hill football team, and 2) wore helmets that were already equipped with Head Impact Telemetry (HIT) System accelerometers during practices and games. See Table 1 for demographics information. Recommendations for inclusion were supported by football coaches and sports medicine staff. Exclusion criteria included having a concussive injury within 6 months period prior to the start of the study, a current eye, head or neck injury, or permanent vision loss that may have impaired visual-motor processing performance. Information that was collected prior to data collection included demographics, history of injuries to areas above the shoulders (neck, head, brain, eyes), as well as sleep habits. All study participants provided informed consent prior to the start of the study.

Instrumentation

Head Impact Telemetry System

We used the HIT System (Riddell Corp., Elyria, OH) to collect data including time of impact, impact location, linear acceleration, and rotational acceleration over the course of the season. The HIT System includes in-helmet sensors as well as the Sideline Response System (Riddell Corp., Elyria, OH). Helmets that can be instrumented with sensors include the Riddell Revolution Speed (M, L, XL), and the Riddell Revolution Speed Flex (M, L, XL). Each sensor has 6 single axis accelerometers that record the data, and a memory capacity of approximately 100 impacts. Data are collected at a frequency of 1 kHz for a total of 40 milliseconds.[50] Biomechanical head impact data are then routed to the Sideline Response System (SRS), which is on the field during practices and games, and includes a receiving antenna and a laptop that has Head Impact Telemetry Impact Analyzer software. This software runs the data through an algorithm that calculates impact magnitude and location. Information from 64 helmets can be recorded and viewed in real-time. Data are then stored on a cloud service from where the data are accessible via the secured Riddell Redzone website.

Senaptec Sensory Station

The Senaptec Sensory Station evaluates visual-motor performance in much the same way as the Nike SPARQ Sensory Station did. Promising research has been done using the Nike SPARQ Sensory Station in order to study the relationships between sensory-motor processing and variables such as athletic performance and exposure to severe head impacts.[6,51] The Senaptec Sensory Station consists of many updated and altered tests from its older Nike SPARQ counterpart. Despite the similarities between the two, there needs to be more research on the Senaptec Sensory Station. A description of each of the tests and outcome measures can be found in Table 2.

There is a lack of criterion validity evidence for use of the Senaptec Sensory Station although the logical evidence and construct evidence is strong. The tests are standardized and computerized, and the same instructions will be given by each tester to each participant. The Nike SPARQ Sensory Station has been shown to be reliable, with minimal learning effects.[48]

The Senaptec Sensory Station is made up of three devices: an android tablet, a 55 inch GVision touch screen TV (GVision-USA, Inc.), and an android phone (remote input device). All three of these devices are linked together via Bluetooth or HDMI, and function in sync during the testing. Visual-motor constructs that are tested include visual clarity, contrast sensitivity, depth perception, near/far quickness, perception span, multiple object tracking, reaction time, eye-hand coordination, and go/no-go. Visual clarity, contrast sensitivity, depth perception, and near/far quickness are assessed using the tablet as well as the phone; multiple object tracking and reaction time are assessed using solely the tablet; reaction time is assessed using the TV and the phone; and eye-hand coordination and go/no-go are assessed using solely the touch screen TV. Data from each test are recorded on the Senaptec software located on the tablet, and are eventually backed up to a secure cloud from where they can be accessed via computer.

Procedures

Testing with the Senaptec Sensory Station was performed once in the pre-season (July) and once in the post-season (December). We used the full test battery offered by the Senaptec Sensory Station, as described in Table 2. This involved tests performed on a tablet as well as tests performed on a large touch screen TV and an android phone. In total, the test took approximately 25 minutes, and the participants were instructed to wear any eyewear they normally wear when performing their sport or engaging in physical activity (contact lenses, glasses, etc.). During pre-season testing, each subject was tested by a single administrator. During post-season testing, two test administrators trained on the Senaptec software were present to administer the tests, with one administering the seven tablet tests, and the other administering the three large touch screen tests. Instructions and methods of test administration were identical in pre-season and post-season testing.

The HIT System recorded head impact biomechanics of the football group over the entire season, as well as during pre-season training camp, which began in mid-August. Different helmets were worn for practices versus games, therefore the sensors were moved to the game helmets prior to games, then moved back to the practice helmets. The helmets equipped with sensors were worn every practice and every game of the season, regardless of contact status in practice. The time gates for practice and game sessions were set on site using the HIT Sideline Response System by or under the supervision of a certified athletic trainer via an athletic training student. Reception of accelerometer data by the SRS was verified prior to each practice and game. The data were exported via the Riddell Redzone secure website by our study team. Typically, sensors were assigned to an athlete for the entirety of a season. If any of the sensors were deemed faulty, they were replaced, fixed, and re-assigned to another player. In order to ensure impacts registered on the HIT System were truly due to head impacts on the field, an athletic trainer kept log of what time practices and games started and ended. Despite setting specific time windows, we still picked up some noise, mainly from players on the sideline who would cause helmet impacts without being in play (throwing helmets, etc.).

Data Preparation

Raw data from the HIT System were stored on a secured cloud storage service, and were downloaded at the end of the season. Variables of interest included peak linear acceleration magnitude, and peak rotational acceleration magnitude. As a measure of standard practice, all impacts below 10g were removed.[6] Natural logarithmic transformations were applied to both of these data sets to conform to the assumptions of normality.[52]

Raw data from the Senaptec Sensory Station were also stored on a secured cloud storage service, and were downloaded at the end of post-season testing. Variables of interest included visual clarity, contrast sensitivity, depth perception, near/far quickness, perception span, multiple object tracking, reaction time, eye-hand coordination, and go/no-go.

Statistical Analysis

Specific Aim 1. To test the hypothesis that Division I college football players with poorer preseason visual and sensory performance will demonstrate more severe head impact biomechanics (linear and rotational acceleration) than those with better preseason visual and sensory performance (as measured by the Senaptec Sensory Station).

Our dependent variables for this aim were peak linear acceleration, and peak rotational acceleration. Our independent variables were our ten Senaptec Sensory Tests. We chose to perform twenty separate random intercepts general linear mixed models in order to test the effect of each dependent variable on each independent variable. This model was chosen because it does not assume independence between each data point, it can include incomplete cases, and allows for testing at multiple different time points.

Specific Aim 2. To test the hypothesis that preseason-to-postseason changes in visual and sensory performance are predicted by head impact biomechanic severity in college football players.

Our dependent variables for this aim were the pre- to post-season changes in visual and sensory performance on depth perception, target capture (dynamic visual acuity), perception span, and go/no-go tests. Our independent variables were biomechanical outcome predictors in the form of impact frequency, cumulative peak rotational acceleration magnitude, cumulative peak linear acceleration magnitude, number of impacts above the 90^{th} percentile for peak rotational acceleration, and number of impacts above the 90^{th} percentile for for peak linear acceleration. We chose to perform separate regression analyses for each biomechanical outcome predictor variable because these variables are highly correlated with each other. Furthermore, the regression analysis was selected because we are inferring causation. Our statistical analyses are summarized in Table 3.

CHAPTER IV: MANUSCRIPT

Introduction

With an estimated 1.6 to 3.8 million cases per year, sport-related traumatic brain injury (TBI) is a significant concern for athletes, families, coaches, and medical staff alike.[1] A concussion is a mild form of TBI with transient impairment of neural function that results in decrements in cognition, balance, and vision.[2] High school and college American football has one of the highest concussion incidence rates compared to sports such as soccer, basketball, and others. Therefore, reducing concussion risk, specifically by decreasing the exposure to head impacts, in American football is a significant goal in sports medicine.[3]

Concussions are caused by a combination of linear and rotational forces causing sudden head acceleration/deceleration.[4] Because the brain is enclosed in the skull, limiting its ability to dissipate force, a rapid deceleration can cause large forces to act on the brain, which may cause axonal shearing, metabolic disruptions, and consequent impairments in neural function.[4] Research in the area of head impact biomechanics has yet to find an impact magnitude threshold above which a concussion will occur.[2] However, this literature has revealed a correlation between concussion risk and impact magnitude; the greater the impact, the higher the concussion risk.[5] Thus, reducing high magnitude impacts is believed to lower the overall concussion risk.[5]

Improving an athlete's ability to anticipate an impact may reduce the athlete's exposure to high magnitude impacts, and thus, lower their concussion risk. Anticipating an incoming impact may decrease the overall impact magnitude by activating neck musculature and increasing the head's deceleration time during an impact.[4] Corroborating this hypothesis, anticipated impacts result in less severe head impacts in hockey; however, research conducted in the Division 1 football setting is unclear on the matter.[6,7] It has been hypothesized that impact anticipation involves integration of visual cues and an appropriate motor response.[6,8,] In relation to this, Harpham et al. (2014) observed an association between head impact severity and performance on certain visual-motor tests including perception span, target capture, go/no go, and depth perception. Football players who demonstrated poorer pre-season performance on these functional vision tests sustained more severe head impacts over the course of the following season.[6]

The goal of this study is to build on the results found by Harpham et al. (2014) by doing both pre and post season visual-motor testing. This will allow us to determine whether or not exposure to head impacts over the course of the season will predict pre- to post-season changes in visual-motor processes relative to pre-season measures. There is growing science supporting the theory that visual dysfunction is a more pervasive concussion symptom than once believed.[9] It is possible that exposure to head impacts over the course of a season may cause decreased performance on vision and sensory performance measures. Confirming an association between the two may offer an alternative way of measuring risk for the development of underlying neurophysiological changes purported to accompany late-life and long-term neurological declines associated with football participation.[10]

Methods

Study Design and Participants

This study was a prospective, observational study within a group of college Division I football players. Given the use of continuous variables in this study, and the lack of consensus regarding a cutpoint for identifying individuals with low and high impact exposure, we did not dichotomize our variables to avoid decreasing statistical power of our results.[49]

We recruited 35 male college Division I football players (age = 20.6 ± 1.3 years; height = 188.0 ± 7.1 cm; mass = 109.4 ± 44.3 kg) based on the following inclusion criteria: 1) eligible for unrestricted participation in a Division I college football program, and 2) wore helmets that could be equipped with Head Impact Telemetry (HIT) System accelerometers during practices and games. Exclusion criteria included 1) concussion history within 6 months leading up to the study, 2) a current eye, head or neck injury, or 3) permanent vision loss that may have impaired visual-motor processing performance. Information that was collected prior to data collection included demographics, injury history to areas above the shoulders (neck, head, brain, eyes), as well as sleep habits. All study participants provided informed consent prior to the start of the study.

Instrumentation

Head Impact Telemetry System

We used the HIT System (Riddell Corp., Elyria, OH) to collect data including head impact time, impact location, linear acceleration, and rotational acceleration throughout the season. The HIT System includes in-helmet sensors as well as the Sideline Response System (Riddell Corp., Elyria, OH). Helmets that can be instrumented with sensors include the Riddell Revolution Speed (M, L, XL), and the Riddell Revolution Speed Flex (M, L, XL). Each sensor has 6 single axis accelerometers that record the data, and a memory capacity of approximately 100 impacts. Data are collected at a 1 kHz frequency for a total of 40 milliseconds.[50] These biomechanical head impact data are then routed to the Sideline Response System (SRS), which is on the field during practices and games. It includes a receiving antenna and a laptop that has Head Impact Telemetry Impact Analyzer software. This software runs the data through an algorithm calculating head impact magnitude and location. Information from 64 helmets can be recorded and viewed in real-time. These data are then stored on a cloud service from where they are accessible via the secured Riddell Redzone website.

Senaptec Sensory Station

The Senaptec Sensory Station was developed to assess visual-motor performance in a similar fashion as the Nike SPARQ Sensory Station, with some modifications and updates.[6] Prior research using the Nike SPARQ Sensory Station has found relationships between sensory-motor processing and variables such as athletic performance and exposure to severe head impacts.[6,51] Although most of the Senaptec Sensory Station assessments are are similar to its older Nike SPARQ counterpart, due to the updates and additional tests, more research is needed using the Senaptec Sensory Station to assess visual-motor performance, and its relationship with head impact exposure. A description of each of the tests and outcome measures are in table 2.

There is a lack of criterion validity evidence for use of the Senaptec Sensory Station although the logical evidence and construct evidence is strong. The tests are standardized and computerized, and the same instructions were given by each tester to each participant. The Nike SPARQ Sensory Station has been shown to be reliable, with minimal learning effects.[48] The Senaptec Sensory Station is made up of three devices: an android tablet, a 55-inch GVision touch screen TV (GVision-USA, Inc.), and an android phone (remote input device). All three of these devices are linked together via Bluetooth or HDMI, and function in sync during the testing. The Senaptec Sensory Station testing takes approximately 25 minutes to complete. All the assessment modules are described in Table 2. Data from each test are recorded on the Senaptec tablet software, and are eventually backed up to a secure cloud-based server. The data may be exported directly from the tablet.

Among the tests performed on the Senaptec Sensory Station is the Perception Span task. It assesses visual memory; that is, it assesses how much information can be retained in a very short time span. The task is accomplished by focusing on the screen center and recreating a pattern of dots that are briefly presented to the participant. The assessment employs a staircase algorithm to increase (with correct responses) or decrease (with incorrect responses) the frequency of dot stimuli. Given the spatial pattern and the short time span during which the dotted patterns are presented in the Perception Span task, it is likely that the information is gathered via ambient (peripheral) visual processing. This visual processing system is used when the eye is initially presented with an image and involves short fixations with large saccade amplitudes.[44,45] This process results in an accumulation of rapid, low frequency information from peripheral vision that gives the brain spatial awareness.[45]

Procedures

Testing with the Senaptec Sensory Station was performed once in the pre-season (July, 2017) and once in the post-season (December, 2017). We used the full 10-module test battery offered by the Senaptec Sensory Station, as described in Table 2. Participants were instructed to wear any eyewear they normally wear when participating in football or engaging in physical activity (contact lenses, glasses, etc.). During pre-season testing, each subject was tested by a single administrator. During post-season testing, two test administrators trained on the Senaptec software were present to administer the tests, with one administering the seven tablet tests, and the other administering the last three large touch screen tests. Instructions and methods of test administration were identical in pre-season and post-season testing.

The HIT System recorded head impact biomechanics athletes sustained during the entire season, including the entire pre-season training camp. The helmets equipped with sensors were worn for every game and practice, regardless of contact status in practice. The time gates for practice and game sessions were set on site using the HIT Sideline Response System. Reception of accelerometer data by the SRS was verified prior to each practice and game, and exported to the Riddell Redzone secure website by our study team following each event. Typically, sensors were assigned to an athlete for the entirety of a season.

Data Preparation

Raw data from the HIT System were stored on a secured cloud server, and were downloaded at the end of the season. Variables of interest included peak linear acceleration magnitude, and peak rotational acceleration magnitude. Consistent with published literature in this space, all impacts below 10g were removed.[6] Natural logarithmic transformations were applied to both of these HIT System data sets to conform to the assumptions of normality.[52] Raw data from the Senaptec Sensory Station were also stored on a secured cloud server, and were downloaded at the end of post-season testing. Variables of interest included visual clarity, contrast sensitivity, depth perception, near/far quickness, perception span, multiple object tracking, reaction time, target capture, eye-hand coordination, and go/no-go.

Statistical Analysis

In a series of separate random intercepts general linear mixed models, we tested whether preseason Senaptec test outcomes predicted either peak linear acceleration or peak rotation acceleration. For our second hypothesis, we ran a series of general linear models to test the effect of in-season head impacts on pre- to post- season changes in visual and sensory performance. In separate models, we tested the effect of one of five head impact predictors (impact frequency, cumulative peak rotational acceleration magnitude, cumulative peak linear acceleration magnitude, number of impacts above the 90^{th} percentile for peak rotational acceleration, and number of impacts above the 90^{th} percentile for for peak linear acceleration), on one of four Senaptec change scores of interest (depth perception, target capture, perception span, and go/no-go). We chose to perform separate regression analyses for each biomechanical outcome predictor variable due to high multicollinearity among these variables. Our statistical analyses are summarized in Table 3. We also performed paired samples t-tests for each Senaptec test outcome in order to compare pre- and post-season mean performance, which are summarized in Table 7.

Results

Table 1 summarizes the participant demographics for this study while Table 8 summarizes participant demographics and head impact data by position group. Several participants were excluded due to injuries during the season or lack of data. Initial pre-season tests were completed for 35 participants. Pre-season data for one of the participants were lost due to a technical issue with the data collection platform. Of the 34 remaining participants, five participants did not contribute head impact data, resulting in a final sample of 29 with both pre-season visual-motor performance testing and in-season head impact data. Post-season data for another participant participant were lost due to a technical issue with the data collection platform, and another two participants did not complete post-season visual-motor performance testing resulting in a final sample of 26 athletes who had both pre- and post-season Senaptec data as well as head impact biomechanic data. Five of these sustained concussions during the season, requiring further consideration during data analysis.

Our series of random intercept general linear mixed models testing the effect of pre-season visual and sensory performance on head impact biomechanics indicated that performance on the depth perception task with primary gaze, and performance on the depth perception task with right gaze significantly predicted peak linear acceleration [depth perception, primary gaze: $F_{1,27} = 9.12$, $p=0.006$, $\beta=1.00$; depth perception, right gaze: $F_{1,27} = 15.90$, $p<0.001$, $\beta =1.00$]. Specifically, on average athletes with poorer performance (increased score) on either of these tasks had higher peak linear accelerations. None of the other Senaptec Sensory Station task scores significantly predicted linear or rotational acceleration magnitudes ($P>0.05$), but some approached significance. These includes contrast sensitivity at 18 cycles/degree predicting linear rotation ($F_{1,27}$= 3.55, p=0.070, β = -1.09), depth perception (primary gaze) predicting rotational acceleration ($F_{1,27}$= 3.22, p= 0.084, β =1.00), and perception span score predicting rotational acceleration ($F_{1,27}$= 3.10, p= 0.090, β =1.00).

Our regression analyses testing the effects of head impact biomechanics on pre to post-season changes in visual-motor performance showed that frequency of impact [β= -1.03, p<0.01, R^2= 0.35], cumulative peak linear acceleration [β= -1.00, p<0.01, R^2= 0.36], cumulative peak rotational acceleration [β= -1.00, p<0.01, R^2= 0.33], number of impacts above the 90th percentile of linear acceleration [β= -1.24, p= 0.01, R^2= 0.30], and number of impacts above the 90th percentile of rotational acceleration [β= -1.19, p= 0.04, R^2= 0.21] were all statistically significant predictors of pre to post-season decrements in performance on the Perception Span task. These results are summarized in Table 4. These analyses showed that head impact biomechanics did not predict changes in Depth Perception [frequency on depth perception (right gaze): β= -1.04, p= 0.188, R^2= 0.09; cumulative peak linear acceleration on depth perception (right gaze): β= -1.00, p= 0.171, R^2= 0.10; cumulative peak rotational acceleration on depth perception (right gaze): β= -1.00, p= 0.249, R^2= 0.07; number of impacts above the 90th percentile of linear acceleration β= -1.51, p= 0.158, R^2= 0.11; number of impacts above the 90th percentile of rotational acceleration β= -1.31, p= 0.329, R^2= 0.05], Target Capture, or Go-No-Go tasks. When excluding participants who sustained in-season concussions, the regression analyses also showed that frequency of impact [β= -1.03, p<0.01, R^2= 0.42], cumulative peak linear acceleration [β= -1.00, p<0.01, R^2= 0.40], cumulative peak rotational acceleration [β= -1.00, p<0.01, R^2= 0.40], number of impacts above the 90th percentile of linear acceleration [β= -1.25, p= 0.02, R^2= 0.33], and number of impacts above the 90th percentile of rotational acceleration [β= -1.20, p= 0.05, R^2= 0.25] were statistically significant predictors of pre to post-season decrements in performance on the Perception Span task. These results are summarized in Table 5.

Discussion

Our main findings were twofold: performance on pre-season depth perception tasks were significant predictors of peak linear acceleration (aim 1); and head impact frequency and severity were significant predictors of pre to post-season changes in performance on a Perception Span task in college football players (aim 2). Poor performance on pre-season depth perception tasks predicted an increased peak linear acceleration, which was in line with our hypothesis that Division I college football players with poorer pre-season visual-motor performance would demonstrate more severe head impact biomechanics. Contrary to what we hypothesized, none of the other visual-motor performance tasks significantly predicted head impact biomechanics.

Higher frequency and severity of impacts throughout the season (as measured by sum of linear accelerations, sum of rotational accelerations, and number of impacts above the 90th percentile of both rotational and linear acceleration) predicted a lower score on the post-season Perception Span task relative to pre-season testing. Sustaining a high number of impacts with linear or rotational accelerations above the 90th percentile predicted the largest decrease from pre to post-season performance of Perception Span. These results were maintained in the study group as a whole, as well as in the group with no in-season concussions. The average collegiate football play lasts approximately 5 seconds during which time offensive and defensive schemes need to be seen and memorized (using working visual memory), processed, then acted on, all while allowing for adjustments based on what happens after the ball is snapped. Working visual memory is defined as "the active maintenance of visual information to serve the needs of ongoing tasks", and is recognized as being important to sports performance.[53,54] Given that performance on the Perception Span requires the use of working visual memory, a decrease in performance on this task could have negative effects on sports performance, and injury avoidance. Peripheral visual processing, which is involved in the visual integration portion of working visual memory has also been shown to be related to performance in various sports, and may also be just as important in football.[51,55] The results we observed agreed with our hypothesis that high severity subconcussive head impacts can have negative effects on visual-motor performance. It is worth noting that head impact biomechanics did not predict a pre to post-season change in performance on the Depth Perception, Target Capture, and Go-no-go tasks.

Variables that were statistically significant predictors of decreased visual-motor performance included impact frequency, cumulative peak linear acceleration, cumulative peak rotational acceleration, and number of impacts above the 90th percentile for linear and rotational acceleration (see Tables 4 and 5). Despite the statistical significance of these predictions, the explained variability of these models ranged from 21% to 42%. This means there could be factors we did not account for in our mathematical models that were also contributing to these pre- to post- season changes. Our observed prediction of decrease in visual-motor performance due to repeated sub-concussive head impacts may be explained by previously observed neural changes due to repetitive sub-concussive impacts in football players.[13] A study from 2014 observed neural changes in players following a season of collegiate football that lasted even after 6 months of rest.[13] Future research should try to determine if decrements in visual-motor performance due to increased head impact severity can also be observed after 6 months of rest.

While this relationship wasn't observed in our study, previous research in the football setting has shown poor performance on computerized Perception Span tasks to predict high head impact severity.[6] The question which still remains is whether or not poor performance on perception span tasks predict increased head impact severity at the same time that increased increased head impact severity predicts a decrease in perception span task performance. If both occur simultaneously, this could create a cycle leading to long term decreased visual memory and spatial awarenes.[44,45] Given that visual memory and spatial awareness may be key to football performance as well as anticipation of impending impacts, further research should use event footage to identify situations where high accelerations impacts ocur.[51,55]

We found that poor pre-season performance on Depth Perception tasks were significant predictors for increased head impact severity as measured by cumulative linear acceleration. These results agreed with our hypothesis that poor pre-season visual-motor performance can predict an increased severity of head impacts throughout the course of a football season, but no other measures of visual-motor performance showed significant predictions for head impact biomechanics. The Depth Perception task on the Senaptec Sensory Station is a measure of stereopsis where binocular vision is used by the brain to create a perception of depth. It involves looking at the tablet screen that is showing 4 rings while wearing red-cyan anaglyph glasses, and swiping (on the remote input device) in the direction of the ring that appears to be at a different depth than the others. This task is performed under three different viewing conditions: facing forward (primary gaze), looking over the right shoulder (right gaze), and looking over the left shoulder (left gaze). Performance on the task while facing forward and while looking over the right shoulder were both predictors for increased severity of head impacts.

While the literature on sports performance in relation to depth perception is divided, this study is the second to observe that decreased computerized depth perception task performance predicted an increased head impact severity in collegiate football athletes.[6,48] Previous research has also shown that athletes with a history of concussion show decreased performance on depth perception tasks compared to athletes with no history of concussion.[56] An athlete's inability to accurately perceive differences in depth (among other visual-motor processes) could have a lasting impact on sports performance, but more importantly, an inability to properly judge how close an opponent is could have an impact on their ability to anticipate impacts, and in turn have a negative influence on head impact severity.[2,4] Interestingly, the study of depth perception may provide insight into a factor of anticipation that is rarely studied in the context of sports injuries: timing. An inability to appropriately perceive depth, despite having all moving pieces in one's visual field, could lead to misjudging timing of impact, resulting in an inability to brace for, or avoid impact. This could lead to an increased risk of injury, which was shown in this study in the form of increased head impact severity. Research into the relationship between depth perception, anticipation, and timing is warranted, as is research into the potential preventative effects of computerized training of depth perception.

Limitations

Participant attrition due to unwillingness to perform post-season Senaptec Sensory Station testing caused a reduction in our intended sample size. Enrolling a much larger number of participants would help mitigate the effects of this potential data loss. Head impact biomechanics data was recorded from the HITS System based on specific time gates assigned for each event. Despite this, we still picked up some noise, mainly from players on the sideline or in the locker room who would cause helmet impacts without being in play (throwing helmets, etc.). This noise only represented a small percentage of the data that was collected by the HITS system. In regards to overall study design, a non-contact control group of football players was not available for this study, but our models regressed for impact exposure, which included both athletes with fewer and athletes with greater head impact frequency and severity. Subsequent research should aim to include two groups with large sample sizes including a control group composed of competitive, non collision sport individuals, in order to evaluate the test-retest reliability of the Senaptec Sensory Station.

Conclusion

While our findings did agree with a previously identified link between visual-motor performance and head impact biomechanics in college football athletes where decreased visual-motor performance predicted increased severity of head impact biomechanics, performance on a majority of the visual-motor tasks we tested did not show a significant prediction.[6] Our findings also revealed a predictive relationship between head impact severity and visual-motor performance where an increase in head impact severity over the course of a season caused a decrease in pre- to post-season visual-motor performance. Head impact severity did not significantly predict pre- to post-season changes in any other visual-motor performance tasks. We have yet to determine to what extent subtle decreases in visual processing affect performance and ability to anticipate impacts. A small decrease in visual-motor processing could be meaningful given the majority of sensory input the body receives is by way of the visual system. This is a growing area of clinical interest, and we are still unable to fully answer questions regarding the best way of reducing injury risk, but decreasing exposure to head impacts and increasing anticipation and visual-motor function may be important steps in doing so.[5,8]

Table 1. Participant Demographic Information at Baseline

	All participants	Non-concussed	Concussed[a]
	Mean (SD)[b]	Mean (SD)[b]	Mean (SD)[b]
Age (years)	20.6 (1.3)	20.7	20.4 (1.1)
Height (cm)	188.0 (7.1)	188.6 (7.1)	186.1 (6.8)
Mass (kg)	109.4 (44.3)	110.9 (19.4)	104.2 (23.0)
Football Experience (years)	11.4 (3.3)	11.2 (3.5)	12.0 (2.1)
Concussions History (number)	0 (0 – 4)	1 (0 – 4)	0 (0 – 3)

[a] Concussed group represents those healthy athletes initially enrolled in the study who subsequently sustained a concussion during the study season.
[b] Concussion history is not reported as mean (SD), but as median (range)

Table 2. Senaptec Sensory Station Evaluation Procedures

Test	Description	Participant Set-Up	Procedures
Visual Clarity (LogMAR ; 20/20 vision = value of 0)	How clearly athletes see distant details.	Participant stands 10ft away from Senaptec tablet, holding Senaptec remote input device, and vision occluder.	Black Landolt rings (C-shaped ring) with gaps at the top, bottom, left, and right appeared in random order on a white background. The participant is instructed to swipe the screen of the remote input device in the direction of the opening of the Landolt ring. The rings are preset at varying acuity demands. The procedures include monocular assessments followed by a binocular assessment. The participant isolates each eye with a vision occluder when prompted.
Contrast Sensitivity (Log CS = -log(/threshold))	Ability to pinpoint subtle differences in contrast.	Participant stands 10ft away from tablet, holding remote input device.	Four black circles are presented on a light background. At random, one of the circles will contain a pattern of rings. The participant is instructed to swipe the screen of the remote input device in the direction of this circle.
Depth Perception (Arcseconds)	Accuracy in judging 2-eyed depth information through multiple gaze positions.	Participant stands 10ft away from tablet facing tablet, wearing red-cyan anaglyph glasses and holding remote input device.	The red-cyan anaglyph glasses simulate depth in one of the four rings that appear on the screen. The participant is instructed to swipe the screen of the remote input device in the direction of the ring that appears closest. Test procedures are repeated standing to the side looking over both left and right shoulders.
Near-Far Quickness (# of cycles the participant completed)	Ability to quickly & accurately change visual attention between near and far distances.	Participant stands 10ft away from tablet, holding remote input device.	A series of black Landolt rings appear, alternating between the remote input device screen and the screen on the tablet display. The participant is instructed to swipe the screen of the remote input device in the direction of the opening of the Landolt ring
Perception Span (# of correctly identified circles)	Accuracy of visual memory (obtaining critical visual information)	Participant stands 2ft away from tablet.	The participant focuses on a dot in the center of a grid pattern composed of up to 30 circles. A pattern of dots flash within the grid. The participant then attempts to replicate the pattern on the tablet screen.
Multiple Object Tracking (Max # tracked circles; max rotation speed)	Accuracy in tracking multiple objects moving at varying speeds.	Participant stands 2ft away from tablet.	The participant focuses on a central point of the screen. 2 to 5 sets of circles appear on the tablet screen. One dot of each pair briefly flashes red. The dots then rotate around each other at varying speeds. Once the dots are immobile, the participant is instructed to select the dot in each pair that flashed red at the beginning of the test.
Reaction Time (Time (ms))	Duration of time it takes an individual to accurately respond to a visual stimulus with their hand.	Participant stands 2ft away from tablet.	Two annular patterns appear on the screen. The participant places their index fingers on the inner circle of each pattern, and focuses on the center of the annular pattern in front of them. After a random delay of 2, 3, or 4s, one or both patterns turn red, prompting the athlete to remove the required index finger(s) as quickly as possible.
Target Capture (Response time (ms))	Ability for rapid visual shifting and recognition of peripheral targets.	Participant stands 10ft from 55 inch GVision-USA, Inc. touch screen. connected to tablet, holding remote input device.	The participant focuses on a central black dot on the large Senaptec Sensory Station display until a black Landolt ring appears briefly in one of the corners. The participant is instructed to swipe the screen of the remote input device in the direction of the opening of the Landolt ring.
Eye-Hand Coordination (Average time to touch each target (ms))	Ability to make quick and accurate visually-guided hand responses to rapidly changing targets.	Participant stands 2ft away from 55 inch GVision touch screen connected to tablet.	A grid composed of ten columns and eight rows of equally sized and spaced circles fills the screen of the Senaptec Sensory Station display. In a pseudorandomized order, a circle of the grid turns green. The participant is instructed to touch the green circle as quickly as possible with either hand. As soon as they do, another circle turns green.
Go/No Go (Number of correct hits; Number of incorrect hits, Correct hits – incorrect hits)	Quick & accurate decision responses to rapidly changing targets.	Participant stands 2ft away from large touch screen connected to tablet.	A grid identical to the Eye-Hand Coordination test appears on the screen. A pseudorandomized sequence of green and red dots appears. The participant is instructed to touch green circles as quickly as possible, but avoid touching red circles. All circles disappear after 500ms.

Table 3. Data Analysis Summary

	Aims	Variables	Comparison	Method
1	To test the hypothesis that Division I college football players with poorer preseason visual and sensory performance will demonstrate more severe head impact biomechanics (linear and rotational acceleration) than those with better preseason visual and sensory performance (as measured by the Senaptec Sensory Station)	**Independent Variables:** Senaptec Sensory Station Outcome measures (17) **Dependent Variables:** 1) Linear acceleration 2) Rotational acceleration	Visual-sensory performance measures Head impact exposure severity	Random intercepts general linear mixed models
2	To test the hypothesis that preseason-to-postseason changes in visual and sensory performance are predicted by head impact biomechanic severity in college football players.	**Independent Variables:** 1) impact frequency 2) cumulative peak rotational acceleration magnitude 3) cumulative peak linear acceleration magnitude 4) number of impacts above the 90th percentile for peak rotational acceleration 5) number of impacts above the 90th percentile for for peak linear acceleration **Dependent Variables:** Pre- to post-season changes in the following visual sensor performance measures: 1) depth perception 2) target capture 3) perception span 4) go/no-go	Change in visual-sensory performance measures Head impact exposure severity	Regression Analysis

Table 4. Simple Linear Regression Models Addressing Change in Vision Performance as Predicted by Head Impact Variables: All Participants

	Pre to post season change in Perception Span (All Participants)		
Univariate Predictor	**Slope**	**Significance (p value)**	**R^2**
Frequency of impacts	- 1.03	<0.01	0.35
Cumulative peak linear acceleration	- 1.00	<0.01	0.36
Cumulative peak rotational acceleration	- 1.00	<0.01	0.33
Impacts above the 90^{th} percentile (linear acceleration)	- 1.24	0.01	0.30
Impacts above the 90^{th} percentile (rotational acceleration)	- 1.19	0.04	0.21

Table 5. Simple Linear Regression Models Addressing Change in Vision Performance as Predicted by Head Impact Variables: Non-Concussion Group

	Pre to post season change in Perception Span (Non-Concussion Group)		
Univariate Predictor	**Slope**	**Significance (p value)**	**R^2**
Frequency of impacts	- 1.03	<0.01	0.42
Cumulative peak linear acceleration	- 1.00	<0.01	0.40
Cumulative peak rotational acceleration	- 1.00	<0.01	0.40
Impacts above the 90^{th} percentile (linear acceleration)	- 1.25	0.02	0.33
Impacts above the 90^{th} percentile (rotational acceleration)	- 1.20	0.05	0.25

Table 6. Simple Linear Regression Models Addressing Change in Vision Performance as Predicted by Head Impact Variables: In-Season Concussion Group

	Pre to post season change in Go/No-go total score (In-Season Concussion Group)		
Univariate Predictor	**Slope**	**Significance (p value)**	R^2
Impacts above the 90th percentile (linear acceleration)	1.06	0.04	0.80

Table 7. Pre to Post-season Mean Senaptec Sensory Station Performance Comparison

Senaptec Sensory Station Test	Pre-Season Measures	Post-Season Measures	t-value	P-value
Visual Clarity (right) (N=23)	-0.08 ± 0.14	-0.08 ± 0.17	0.001	0.999
Visual Clarity (left) (N=23)	-0.11 ± 0.17	-0.09 ± 0.12	-0.582	0.567
Visual Clarity (both) (N=23)	-0.17 ± 0.11	-0.13 ± 0.09	-1.228	0.232
Contrast Sensitivity (6) (N=23)	1.96 ± 0.19	2.04 ± 0.17	-1.779	0.089
Contrast Sensitivity (18) (N=23)	1.58 ± 0.26	1.60 ± 0.18	-0.336	0.740
Depth Perception (P) (N=23)	180.13 ± 81.90	191.78 ± 65.55	-0.582	0.567
Depth Perception (R) (N=23)	187.09 ± 66.03	225.17 ± 44.41	-3.215	0.004
Depth Perception (L) (N=23)	212.04 ± 53.83	215.61 ± 48.20	-0.325	0.748
Near Far Quickness (score) (N=23)	26.17 ± 5.78	28.52 ± 5.35	-1.814	0.083
Perception Span (score) (N=23)	39.22 ± 13.05	41.70 ± 18.03	-0.641	0.528
Multiple Object Tracking (prop score) (N=23)	0.73 ± 0.11	0.76 ± 0.09	-1.244	0.227
Multiple Object Tracking (comp score) (N=23)	1696.98 ± 523.78	1799.12 ± 469.96	-0.774	0.447
Reaction Time (average score) (N=23)	304.78 ± 28.64	303.39 ± 29.19	0.255	0.801
Target Capture (score) (N=28)	201.79 ± 87.91	196.43 ± 69.96	0.261	0.796
Eye Hand Coordination (total time) (N=27)	48291.93 ± 2789.85	47273.96 ± 2555.46	1.708	0.100
Eye Hand Coordination (average RT) (N=27)	654.86 ± 34.76	642.94 ± 31.95	1.595	0.123
Go-No-Go (total score) (N=27)	9.04 ± 4.32	12.63 ± 5.29	-4.035	0.000

Table 8. Participant Descriptives and Mean Linear and Rotational Acceleration by Position Group

	n	Age, yr	Height, cm	Mass, kg	Linear Acceleration, g	Rotational Acceleration, rad/s^2
Bigs[a]	10	20.8 ± 1.40	194.44 ± 4.73	132.40 ± 12.09	27.44 ± 18.42	1191.73 ± 903.49
Big Skill[b]	7	20.71 ± 0.76	187.96 ± 3.88	105.88 ± 7.44	27.31 ± 19.20	1273.02 ± 980.75
Skill[c]	9	20.11 ± 1.37	181.75 ± 5.41	88.3 ± 7.32	25.11 ± 17.65	1105.81 ± 833.42
Special Teams[d]	4	20.75 ± 1.26	187.96 ± 4.15	103.42 ± 7.11	29.71 ± 26.74	1171.06 ± 1165.11
Total	30	20.57 ± 1.22	188.26 ± 6.8	109.12 ± 20.14	27.07 ± 19.09	1192.56 ± 928.43

[a] Bigs: offensive linemen, defensive linemen.
[b] Big skill: quarterbacks, linebackers, tight ends.
[c] Skill: defensive backs, running backs, wide receivers.
[d] Special teams: kickers, long snappers.

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