HEAD IMPACT EXPOSURES AND NEUROLOGIC FUNCTION IN
COLLEGE FOOTBALL AND SOCCER PLAYERS

by

Chelsea Best

A thesis submitted to the Faculty of the University of Delaware in partial fulfillment
of the requirements for the degree Master of Science in Exercise Science

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Chelsea Best

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# TABLE OF CONTENTS

LIST OF TABLES ................................................................................................................ v

ABSTRACT ....................................................................................................................... vi

Chapter

  1 INTRODUCTION ........................................................................................................ 1
  2 METHOD .................................................................................................................... 6
  3 RESULTS ................................................................................................................... 14

  4 DISCUSSION ............................................................................................................ 21

REFERENCES ............................................................................................................... 28

Appendix

  A LITERATURE REVIEW ...................................................................................... 39
  B IRB APPROVAL LETTER ..................................................................................... 72
LIST OF TABLES

Table 2.1: Participant Demographics ............................................................................... 13
Table 3.1: Mean Impacts by Sport................................................................................... 19
Table 3.2: Overall Test Means by Time........................................................................... 20
Table 3.3: Overall Mean Head Impact Kinematics .............................................................. 20
ABSTRACT

Objective: To examine the relationship between repeated head impacts and neurologic function through a clinical multifaceted testing battery over the course of one season in both male collegiate football players and female collegiate soccer players.

Subjects: Thirty eight National Collegiate Athletic Association (NCAA) Division I athletes were used during this study. Two groups were broken into fifteen male (20.5±1.1 y/o, 186.4±7.3 cm, 107.3±17.1 kg) and eighteen female (19.4±1.2 y/o, 167.6±4.2 cm, 61.2±5.4 kg) student athletes

Design and Setting: This was a prospective longitudinal study. Associations between sport and time were calculated by a 2x2 repeated measures ANOVA. A total of 9 ANOVAs were performed with a simple linear regression used to evaluate head impact kinematics (number of impacts, cumulative impacts, mean linear acceleration). Testing occurred prior to the start of preseason and within one week after the end of the season for each team.

Measurements: Testing consisted of the Standardized Assessment of Concussion (SAC), Balance Error Scoring System (BESS), King-Devick (KD), Clinical Reaction Time (CRT), and Immediate Post-Concussion Assessment and Cognitive Testing (ImPACT). Football and women’s soccer head impacts and accelerations were measured through the Head Impact Telemetry System (HITS) sensors and Triax system head accelerometers, respectively.
**Results:** There were no significant differences for either sport when comparing pre-season to post-season test scores. No predictive values were significant after the course of a full season for either sport. Our results calculated 4,178 impacts total for all football participants and 3,176 cumulative impacts for all women’s soccer participants, with mean accelerations of 23.8g and 16.3g, respectively.

**Conclusions:** Future research is needed to assess prolonged participation over multiple seasons in male and female contact sports and the risk of neurocognitive deficits after multiple seasons. One athletic season may not be long enough to determine any deficits through a concussion assessment battery.

**Key words:** repetitive head impacts, neurocognitive function, test battery, concussion assessment
Chapter 1

INTRODUCTION

Concussions have been estimated to reach numbers between 1.6 and 3.8 million annually in the United States, accounting for 5-9% of all sports related injuries.\textsuperscript{1,2} Concussions have become a popular topic within sports medicine, particularly due to the unknown nature of long term neurologic effects. However, research is showing that repeated head impacts may play an equal, if not larger, role in longer term neurological decline.\textsuperscript{3-5} These repeated head impacts are cranial impacts that do not result in known or diagnosed concussion on clinical grounds.\textsuperscript{6} A “slosh” phenomenon exists when a rapid acceleration-deceleration of the body or torso occurs when the brain moves within the cranium.\textsuperscript{6} Symptoms may not develop and there are no outward or visible signs of neurological dysfunction.\textsuperscript{7} The greatest deficits may occur from repetitive occurrences and the resultant long term cumulative exposures.\textsuperscript{7} Long careers within high impact sports that lead to repetitive head trauma may result in diminished cerebral reserve and earlier expression of neurodegenerative disorders like Alzheimer’s disease and Chronic Traumatic Encephalopathy (CTE).\textsuperscript{8-10}

Although long term effects have been well documented, albeit with uncertain mechanisms and in limited populations, there are still questions surrounding shorter term effects with athletics and sport participation. One regular full season of collegiate football lasts up to fourteen weeks including two weeks of preseason and one bye week. Collegiate
women’s soccer seasons last up to thirteen weeks, including two weeks of preseason. The opportunity of post-season play could also increase the length of the season for both teams. Currently, however, there are inconsistent findings related to neurological function and repeated head impacts. Some studies have found neurologic decline amongst high school athletes after fMRI was used after a full athletic season. The imaging used was both sensitive and valid and could detect smaller changes than clinical baseline concussion assessments, however the clinical meaningfulness of these findings is still to be determined. The imaging used is also not feasible for use during all concussion testing because they are normally expensive and time consuming, as well as ongoing questions on the importance of the imagining outcomes and limited utilization of control groups. Other studies have used feasible clinical testing that is part of a standardized concussion test battery, but found no neurologic differences. Utilizing a multidimensional concussion assessment test battery assesses more domains of neurologic function, including cognition, balance, oculomotor function and reaction time than singular tasks; they are recommended for the evaluation, diagnosis, and management of sport related concussions and not just the reliance on one singular test. Studies that used these test batteries mainly looked at domain of cognition and have not used multifaceted testing batteries to describe neurologic function.

Most studies examining the effect of head impacts have focused on collision sports such as football and ice hockey. This is due to the nature of both respective sports with more collisions leading to more head impacts. Recent studies have found
football to have the one of the highest overall rates of concussion (67.1/100,000 exposures) and highest annual reported concussions (3,417) within all National Collegiate Athletic Association (NCAA) sports teams. The average impact for collegiate football is estimated to be between 21-23g and can range from 200 to 1,000 per player each year. Head impact magnitudes and frequencies are found to be higher during full contact practices than games and scrimmages.

Because football has one of the highest rates of concussion, and potential cumulative damage of repeated head impacts, the NCAA implemented a series of practice guidelines, not requirements that recommend a limited number of full “live” contact days during the course of a pre and regular football season. The preseason is limited to four live practices per week with a maximum of twelve for the duration of preseason; three scrimmages would allow for additional live practices. No more than two live practices are allowed per in-season practice week, along with postseason practice schedules for all levels of collegiate football. Spring season practices also have restrictions, including only two live practices per week, a maximum of eight live practices overall, and three scrimmages. It is also required of bigger Power Five schools to have a “head trauma reduction” plan that attempts to limit and reduce the amount of head impacts. Even with restrictions on practices and impacts, football is still a high risk sport that may continue to predispose individuals to long term effects.
over the course of an athletic career and more information still needs to be learned about these changes.

Few studies have examined the effects of head impacts on female sports, specifically soccer. Women’s soccer accounts for the highest number of head impacts and concussions among female athletes. It has one of the highest number of annual reported concussions (1,113) and a high overall rate of concussion (63.1/100,000 exposures). Female athletes have performed worse than male athletes on visual memory and report more symptoms after a concussion, but were similar to male athletes at baseline. Female athletes also displayed greater changes from baseline cognitive performance than male athletes. Gender differences may be attributed to psychological reasons, hormonal systems, and musculature. Collegiate women’s soccer athletes sustain up to 1,703 impacts during a season, with 90% associated with heading the ball. Collegiate athletes sustain an average of 3.52 impacts per practice and 6.98 impacts per game. Total overall impacts range from 1.86 to 4.59 impacts. However, teams may have different preferences of ball handling and could head more than others. To date, no studies have examined the effect of these repeated impacts in women’s soccer on neurologic function over the course of an athletic season.

Therefore, the purpose of this study is to examine the relationship between repeated head impacts and neurologic function through a clinical multifaceted testing battery and head impact accelerometers over the course of one season in both male
collegiate football players and female collegiate soccer players. The first aim will determine if the testing battery differs by group or time over the course of an athletic season. We hypothesize that there will be a difference between pre and post-season test scores, along with differences between groups for all tests, but football will have more overall decreased scores than women’s soccer during post-season testing. This would be due to the higher amount of head impacts sustained during the football season as compared to the women’s soccer season. The second aim determines how well head impact kinematics predict neurological deficits in both football and women’s soccer through the use of accelerometers. We hypothesize that head impact kinematics will predict neurological deficits in both football and women’s soccer.
Chapter 2
METHOD

Participants

This study recruited thirty one National Collegiate Athletic Association (NCAA) Division I student athletes. The first group were 14 male student-athletes who were active members of the football team (FB) and instrumented with HITS system (Table 2.1). The second group were 17 female student-athletes who were active members of the women’s soccer team (WSOC) and instrumented with Triax head accelerometers (Table 2.1). Not surprisingly, the FB participants were significantly taller and heavier than the WSOC participants. Participants were included if they were medically cleared for full unrestricted athletic participation on the day of testing and had not suffered a concussion within the previous 60 days. Participants who sustained musculoskeletal injuries, but were still listed as full participation at the conclusion of the season were included in the study. Exclusion criteria was any condition that restricted medical clearance at either time of testing. All participants provided oral and written consent as approved by the University of Delaware’s institutional review board.

Methods

Participants were tested on two occasions: 1) during the summer prior to the start of preseason and 2) within one week after the end of the season for each team. During the summer, athletes for both sports were already on campus participating in non-mandatory sport conditioning and lift activities. Testing consisted of the
Standardized Assessment of Concussion (SAC), Balance Error Scoring System (BESS), King-Devick (KD), Clinical Reaction Time (CRT), and Immediate Post-Concussion Assessment and Cognitive Testing (ImPACT). All pre-season tests were performed in random order in the same testing session and conducted by an experienced clinician. During post-season testing, the same tests were again administered to the athletes in random order and by an experienced clinician. The testing battery was designated by a larger study the institution was participating in.

The HITS (Simbex, Lebanon, NH, USA) is a wireless system that provides real-time impact kinematics of impacts from each monitored player within their helmets. The system contains six single axis spring loaded accelerometers that record impact kinematics and are specifically designed to fit into Riddell helmets. They also contain a wireless transceiver and on-board memory. They are inserted into each individual helmet and maintain constant contact with the head to ensure measurements are of head accelerations rather than helmet. The data is transmitted to the Sideline Response System (Riddell Corp., Rosemont, IL, USA) where it is processed with the threshold to record data set to 10g. Any impact exceeding this threshold provided 40ms of data; 8ms prior to the impact and 32ms post-impact. Each individual accelerometer can store up to 100 impacts on a downloadable memory card if out of range from the sideline system. Following the conclusion of the season, the number of impacts, cumulative linear acceleration and mean linear acceleration were extracted for each participant.
The Triax (Norwalk, CT, USA) system head accelerometers measures head impacts sustained during play in real time for non-helmeted sports. A Smart Impact Monitor (SIM) comprised of a high-g 3-axis accelerometer, low-g 3-axis accelerometer, rechargeable lithium ion battery and 900 MHz radio was used to collect impact data. This SIM measured acceleration levels up to 150g, with a threshold of 10g for recording data. Once an impact was recognized, 10ms before and 52ms post-impact was recorded. WSOC participants wore the accelerometers embedded in headbands during practices and games. The accelerometers were positioned about the nuchal line and below the occipital protuberance on each participant during all play. At the conclusion of the season, number of impacts, cumulative linear acceleration, and mean linear acceleration were extracted.

The Standardized Assessment of Concussion (SAC) is a standardized test used to objectively document the presence and severity of neurocognitive impairment associated with a concussion. It consists of four sections, including orientation, immediate memory, concentration, and delayed recall, to evaluate the cognitive function of those with a suspected concussion. Coordination, sensation and strength are also tested through a neurologic screening portion. It has a maximum total score of 30 points and each incorrect answer results in a loss of one point and a higher score reflects better cognitive performance. It is a reliable, valid, sensitive (.95) and specific (.76) tool for evaluating the neurocognitive deficits sustained during an acute concussion.
The Balance Error Scoring System (BESS) is commonly used for the evaluation of postural stability for post-concussion assessment. The BESS involves three different stances (double limb stance, single limb stance and tandem stance) on two surfaces (firm and foam), where a lower score reflects “better” balance. Each position was held for 20 seconds with the participants’ eyes closed and hands on their hips. Errors were recorded by the administering clinician, which included moving the hands off the hips, opening the eyes, a step, stumble or fall, abduction or flexion of the hip beyond 30 degrees, lifting the forefoot or heel off the testing surface, and remaining out of the proper testing position for greater than 5 seconds and multiple errors occurring simultaneously was scored as a single error. Each stance has a standard maximum error score of ten and thus the total range for scoring was 0–60. Sensitivity for BESS is low (0.34), but specificity values range from .91 to .97 across various time points post-concussion. The reliability of BESS has ranged from poor to good with the minimum detectable change in scores ranging from 7.3 – 9.4 errors.

The King-Devick (KD) Test is a measurement of speed for rapid number naming and reading. It is designed to detect impaired eye movements and saccades; an indication of suboptimal brain function. The test involves reading aloud a series of single-digit numbers from left to right on three test cards as fast as possible. This includes one demonstration card and three test cards that are timed, each increasing in difficulty. Timing starts when the participant begins to read each card and is stopped once they are finished. An error was counted if a number was incorrect or if a number was skipped. Number of errors and overall time for all three cards are combined for
each participant’s score. Each participant was tested twice per session; the fastest time
with fewest errors was recorded as their pre/post season value. The KD test has a
strong reliability (0.97), sensitivity (1.00), and specificity (0.94).

The Clinical Reaction Time (CRT) Ruler Drop Test is a simple measurement
of reaction time. The apparatus used is a 1.3m dowel rod marked in 0.5cm
increments and embedded into a weighted rubber disc 7.5cm wide and weighing 256g.
The weighted disc standardizes the distance the rod falls after release and helps to
ensure the rod will fall nearly vertical when suspended. A lower score is better. A
clinician dropped the ruler and disc at random time intervals varying between two-five
seconds and instructed the participants to grab the ruler as quickly as possible once it
was dropped. Each participant performed two practice trials followed by eight
recorded trials for both dominant (CRTD) and non-dominant hands (CRTND), with
their forearm of the testing hand resting on a flat surface. The equation $d=\frac{1}{2}gt^2$ was
used to calculate the distance in centimeters to time in milliseconds. Test-retest
reliability (0.76 - 0.79) and inter-rater reliability (0.74 - 0.87) were moderate to good
for CRT.

The Immediate Post-Concussion Assessment and Cognitive Testing (ImPACT)
test is a computer-based test that is widely used for assessing neurocognitive function
and concussion symptoms. It is the most widely used computerized testing program in
the sports setting. The ImPACT test focuses on three major categories within the
test; these include demographics, concussion symptoms and neurocognitive tests.
Within the three test categories, six modules evaluate attentional processes, verbal
recognition memory, visual working memory, visual processing speed, reaction time, numerical sequencing ability and learning. These tests include Verbal Memory, Visual Memory, Reaction Time, and Processing Speed. The ImPACT test was administered to each participant individually in a quiet room free from distraction. The four specific tests utilized in this study included Verbal Memory, Visual Memory, Reaction Time, and Processing Speed. Verbal Memory represents word recognition, symbol number match task, and a letter memory task. Visual Memory score is the average percent correct score for two tasks. The first is a recognition memory task that utilizes the discrimination of abstract line drawings and the second is a memory task that identifies specific orders of X’s and O’s after an intervention task. Reaction Time is a score for the average response time (in milliseconds) of a choice reaction time, a go/no-go task and another symbol matching test. Processing Speed represents the composite score for total number of errors of omission or commission on a go/no-go test and choice reaction time test. Combined test sensitivity is 0.81 and specificity is 0.89.

Data and Statistical Analysis

This was a prospective longitudinal study. The independent variables included number of impacts, cumulative linear accelerations, and mean linear acceleration. Dependent variables included SAC, BESS, KD, CRTD, CRTND, and ImPACT scores.

Associations between sport and time were calculated by a 2x2 repeated measures ANOVA using SPSS for Windows version 16.0 (SPSS Inc., Armonk, NY,
USA). A total of 9 ANOVAs were performed. A simple linear regression was used to determine if head impact kinematics (number of impacts, cumulative impacts, mean linear acceleration) were predictors of change in performance from pre- to post-season of the components of the clinical testing battery. Nine linear regressions were performed and all data was expressed as mean ± SD. Level of significance for all comparisons was set as p<0.05.
Table 2.1: Participant Demographics

<table>
<thead>
<tr>
<th></th>
<th>Age (years)</th>
<th>Height (cm)</th>
<th>Weight (kg)</th>
<th>Concussion History</th>
</tr>
</thead>
<tbody>
<tr>
<td>FB</td>
<td>20.5±1.1</td>
<td>186.4±7.3</td>
<td>107.3±17.1</td>
<td>0.5±0.9</td>
</tr>
<tr>
<td>WSOC</td>
<td>19.4±1.2</td>
<td>167.6±4.2</td>
<td>61.2±5.4</td>
<td>0.6±1.1</td>
</tr>
</tbody>
</table>
Chapter 3

RESULTS

Head Impact Exposure

In total, 7,354 total impacts were sustained over the course of a competitive season by the 38 athletes in this study for a total of 151,253.6g. FB sustained a larger amount of impacts, greater cumulative acceleration, and greater average accelerations than WSOC. Overall, the average group total impacts were 220, average group cumulative acceleration was 4,542g, and average group mean linear acceleration was 19.8g. (Table 3.1).

BESS

Differences

There was no significant interaction (p=0.952) for BESS performance. There was significant main effects for group (p=0.002) with WSOC (10.3±6.0) committing significantly fewer errors overall than FB (14.5±6.3). There was a significant main effect for time (p=0.015) with more errors occurring at baseline (13.6±6.4) than post-season (10.3±5.2). (Table 3.2)

Predictability

There was no significant relationship between the combined model and change score for BESS (p=0.625). There was no significant independent relationship between number of head impacts (p=0.281), mean linear acceleration (p=0.670), or linear acceleration (p=0.380). (Table 3.3)
SAC

Differences

There was no significant interaction (p=0.515) for SAC performance. The overall group SAC scores improved from preseason to postseason. There was not a significant main effect for group (p=.499) or for time (p=.515) and there was no significant interaction. (Table 3.2)

Predictability

There was no significant relationship between the combined model and change score for SAC (p=.989). There was no significant independent relationship between number of head impacts (p=0.928), mean linear acceleration (p=0.796), or cumulative linear acceleration (p=0.903). (Table 3.3)

CRTD

Differences

There was no significant interaction (p=0.087) for dominant hand (CRTD) performance. There was not a significant main effect for group (p=.873) or for time (p=.681) and there was no significant interaction. (Table 3.2)

Predictability

There was no significant relationship between the combined model and change score for CRTD (p=.530). There was no significant independent relationship between
number of head impacts (p=0.397), mean linear acceleration (p=0.581), or cumulative linear acceleration (p=0.628). (Table 3.3)

**CRTND**

**Differences**

There was no significant interaction (p=0.473) for non-dominant hand (CRTND) performance. There was not a significant main effect for group (p=.750) or for time (p=.133) and there was no significant interaction. (Table 3.2)

**Predictability**

There was no significant relationship between the combined model and change score for CRTND (p=.744). There was no significant independent relationship between number of head impacts (p=0.353), mean linear acceleration (p=0.285), or cumulative linear acceleration (p=0.344). (Table 3.3)

**KD**

**Differences**

There was no significant interaction (p=0.47) for KD performance. There was a significant main effect for group (p=.017) with WSOC (38.7±6.5) completing a faster time overall than FB (35.6±6.0). There was not a significant main effect for time (p=.110). (Table 3.2)

**Predictability**

There was no significant relationship between the combined model and change score for KD (p=.181). There was no significant independent relationship between
number of head impacts (p=0.348), mean linear acceleration (p=0.232), or cumulative linear acceleration (p=0.141). (Table 3.3)

**ImPACT: Verbal Memory**

**Differences**

There was no significant interaction (p=0.522) for Verbal Memory performance. There was not a significant main effect for group (p=.492) or for time (p=.913). (Table 3.2)

**Predictability**

There was no significant relationship between the combined model and change score for Verbal Memory (p=.607). There was no significant independent relationship between number of head impacts (p=0.789), mean linear acceleration (p=0.469), or cumulative linear acceleration (p=0.841). (Table 3.3)

**ImPACT: Visual Memory**

**Differences**

There was no significant interaction (p=0.839) for Visual Memory performance. There was a significant main effect for group (p=.049) with WSOC (79.0±15.2) scoring lower than FB (85.1±9.0). There was not a significant main effect for time (p=.407). (Table 3.2)

**Predictability**

There was no significant relationship between the combined model and change score for Visual Memory (p=.179). There was no significant independent relationship
between number of head impacts (p=0.386), mean linear acceleration (p=0.654), or cumulative linear acceleration (p=0.813). (Table 3.3)

**ImPACT: Processing Speed**

**Differences**

There was no significant interaction (p=0.661) for Processing Speed. There was not a significant main effect for group (p=.194) or for time (p=.176). (Table 3.2)

**Predictability**

There was no significant relationship between the combined model and change score for Processing Speed (p=.820). There was no significant independent relationship between number of head impacts (p=0.573), mean linear acceleration (p=0.937), or cumulative linear acceleration (p=0.613). (Table 3.3)

**ImPACT: Reaction Time**

**Differences**

There was no significant interaction (p=0.299) for RT performance. There was a significant main effect for group (p=.007) with WSOC (0.53±0.08) completing a faster time overall than FB (0.57±0.08). There was not a significant main effect for time (p=.433). (Table 3.2)

**Predictability**

There was no significant relationship between the combined model and change score for RT (p=.988). There was no significant independent relationship between number of head impacts (r=0.988), mean linear acceleration (p=0.990), or cumulative linear acceleration (p=0.927). (Table 3.3)
<table>
<thead>
<tr>
<th>Position</th>
<th>Total Impacts</th>
<th>Game Impacts</th>
<th>Practice Impacts</th>
</tr>
</thead>
<tbody>
<tr>
<td>OL</td>
<td>505</td>
<td>164</td>
<td>341</td>
</tr>
<tr>
<td>DL</td>
<td>427</td>
<td>16</td>
<td>411</td>
</tr>
<tr>
<td>TE</td>
<td>391</td>
<td>191</td>
<td>200</td>
</tr>
<tr>
<td>OL</td>
<td>357</td>
<td>31</td>
<td>326</td>
</tr>
<tr>
<td>OL</td>
<td>337</td>
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</tr>
<tr>
<td>TE</td>
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<tr>
<td>KRT</td>
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<tr>
<td>LB</td>
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<tr>
<td><strong>Avg. Impact/FB Player</strong></td>
<td><strong>279</strong></td>
<td><strong>80</strong></td>
<td><strong>199</strong></td>
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<td>Goalkeeper</td>
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</tr>
<tr>
<td>Defense</td>
<td>414</td>
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<td>127</td>
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<td>Goalkeeper</td>
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<tr>
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<td>24</td>
<td>15</td>
<td>9</td>
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<tr>
<td><strong>Avg. Impact/WSOC Player</strong></td>
<td><strong>162</strong></td>
<td><strong>85</strong></td>
<td><strong>77</strong></td>
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</table>

*Table 3.1: Mean Impacts by Sport*
<table>
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<tr>
<th></th>
<th>BESS</th>
<th>SAC</th>
<th>CRTD (ms)</th>
<th>CRTND (ms)</th>
<th>KD (sec)</th>
<th>Verbal Memory</th>
<th>Visual Memory</th>
<th>Visual Motor</th>
<th>RT</th>
</tr>
</thead>
<tbody>
<tr>
<td>FPPre</td>
<td>16.1±6.6</td>
<td>27.5±2.2</td>
<td>21.6±5.0</td>
<td>22.0±3.9</td>
<td>37.1±6.4</td>
<td>90.3±8.9</td>
<td>84.1±6.3</td>
<td>43.1±6.4</td>
<td>0.56±0.06</td>
</tr>
<tr>
<td>WSOC Pre</td>
<td>11.9±5.9</td>
<td>27.5±1.9</td>
<td>19.9±3.7</td>
<td>21.5±4.4</td>
<td>39.2±5.1</td>
<td>90.4±10.5</td>
<td>77.4±15.4</td>
<td>44.4±6.2</td>
<td>0.53±0.04</td>
</tr>
<tr>
<td>FPPost</td>
<td>12.8±5.7</td>
<td>27.5±2.0</td>
<td>20.3±3.5</td>
<td>20.0±2.8</td>
<td>34.1±5.4</td>
<td>88.6±8.3</td>
<td>86.1±11.3</td>
<td>40.5±5.6</td>
<td>0.59±0.10</td>
</tr>
<tr>
<td>WSOC Post</td>
<td>8.7±4.4</td>
<td>28.1±2.0</td>
<td>21.6±4.9</td>
<td>21.3±3.8</td>
<td>38.1±4.8</td>
<td>91.6±9.5</td>
<td>80.6±13.4</td>
<td>43.1±6.3</td>
<td>0.53±0.05</td>
</tr>
<tr>
<td>Mean by Time</td>
<td>12.4±2.93</td>
<td>27.67±0.28</td>
<td>20.86±0.18</td>
<td>21.19±0.28</td>
<td>37.15±2.17</td>
<td>90.22±1.11</td>
<td>82.05±4.33</td>
<td>42.77±1.37</td>
<td>0.55±0.03</td>
</tr>
<tr>
<td>Mean by Group</td>
<td>11.96±2.29</td>
<td>27.66±0.26</td>
<td>20.84±0.34</td>
<td>21.23±0.7</td>
<td>37.47±1.3</td>
<td>90.41±0.08</td>
<td>81.3±1.91</td>
<td>43.01±1.32</td>
<td>0.55±0.01</td>
</tr>
</tbody>
</table>

**Table 3.2: Overall Test Means by Time**

<table>
<thead>
<tr>
<th>Overall Mean Change</th>
<th>BESS</th>
<th>SAC</th>
<th>CRTD (ms)</th>
<th>CRTND (ms)</th>
<th>KD (sec)</th>
<th>Verbal Memory</th>
<th>Visual Memory</th>
<th>Visual Motor</th>
<th>RT</th>
</tr>
</thead>
<tbody>
<tr>
<td>3.22±5.6</td>
<td>0.4±2.26</td>
<td>0.32±4.40</td>
<td>0.83±5.55</td>
<td>2.02±3.52</td>
<td>0.31±7.31</td>
<td>-2.14±12.42</td>
<td>-2.18±4.16</td>
<td>-0.01±0.07</td>
<td></td>
</tr>
<tr>
<td>Mean Linear Acceleration (p)</td>
<td>0.67</td>
<td>0.8</td>
<td>0.58</td>
<td>0.29</td>
<td>0.23</td>
<td>0.47</td>
<td>0.65</td>
<td>0.94</td>
<td>0.99</td>
</tr>
<tr>
<td>Total Impacts (p)</td>
<td>0.28</td>
<td>0.93</td>
<td>0.4</td>
<td>0.35</td>
<td>0.35</td>
<td>0.79</td>
<td>0.39</td>
<td>0.57</td>
<td>0.99</td>
</tr>
<tr>
<td>Cumulative Acceleration (p)</td>
<td>0.38</td>
<td>0.9</td>
<td>0.63</td>
<td>0.34</td>
<td>0.14</td>
<td>0.84</td>
<td>0.81</td>
<td>0.61</td>
<td>0.93</td>
</tr>
</tbody>
</table>

**Table 3.3: Overall Mean Head Impact Kinematics**
Chapter 4

DISCUSSION

The main purpose of this study was to examine the neurological changes of both collegiate football and women’s soccer teams after a full athletic season. The primary finding of this study was that there were no significant neurological deficits for either sport when comparing pre-season to post-season test scores. None of the independent variables were significant either in predicting neurologic deficits after a full season for either sport. This is consistent with research that used similar tests in football.\textsuperscript{13,14,51,52} These findings lead to the idea that neurological changes may not occur after a contact sport season for both male and female athletes as measured through this test battery. These results are based off of one season and there is still question about the neurological effects of a long term athletic career.

Our findings are consistent with research that tested pre and post-season with a concussion testing battery without imaging.\textsuperscript{13,52,53} We hypothesized that football athletes would show more neurological deficits than women’s soccer athletes due to the higher number of impacts and higher linear accelerations. Although, football did have more cumulative impacts after their respective season, there was not a significant difference between neurological testing scores. This may be from the similarity among overall impact averages between groups. Individual football participants (79.86) and individual women’s soccer participants (84.67) had close average impacts per player per season. When comparing average impacts per player per game, football (7.27) and women’s soccer (4.42) again were similar. However, football participants (195.77) averaged more practice impacts than women’s soccer
participants (76.89) and more overall average impacts (278.53, 161.56) per participant, respectively. This data shows that although football may have a higher overall impact total per player, both teams have similar overall impact totals per group. This leads to the conclusion that neither group is immediately affected through their neurologic function after one athletic season of high impact and collision sports.

It can be assumed, based off of previous research, that a practice effect may have been present for certain tests and could have had an effect on the testing sessions. All tests utilized for this study were familiar for almost all participants and were part of the standard concussion assessment battery. However, for a majority of the participants, testing only occurred twice during the athletic season at pre-season and post-season. These two time points are nearly six months apart.

Differences have been found in other studies after an athletic season when utilizing neuroimaging techniques, such as functional magnetic resonance imaging. Breedlove found neurological changes within a group of participants who did not present with a diagnosed concussion during testing, but still had noticeable neurological deficits after the end of the athletic season. This lead to the realization of the relationship between the number of blows to the head and the ensuing neurophysiological change. This reinforced the idea of the effects of repetitive head impacts are cumulative and continued exposure to repetitive head impacts is connected to neurophysiological deficits. Talavage noted three distinct groups through their research; one group with no concussion and no neurological changes, a second group that had concussions and changes in neurological behavior, and a third group that did
not have a clinically diagnosed concussion but demonstrated measurable neurocognitive and neurophysiological deficits.\textsuperscript{11} This raises the possibility that traditional concussion assessment testing may not be sensitive enough to detect deficits and impairments among participants or otherwise healthy young adults that have sufficient compensatory strategies to accomplish single task testing.

There has been suggestion of limiting head contact during practices for football as a means to reduce head impact related trauma.\textsuperscript{56} Less impact is assumed to reduce the overall total head impacts, but this is much easier to control in a practice environment than in an unpredictable game situation. The University of Delaware football team had only one live practice each week of the season, less than the allotted two days through the NCAA practice guidelines.\textsuperscript{22} Heading in soccer is also a practiced skill and specific positions will head the ball more than others. Although there are not specific NCAA guidelines for women’s soccer practices, limiting the amount of heading drills could also reduce the amount of overall head accelerations. (Table 3.1) Football linemen and women’s soccer goalkeepers and defensive players sustained the most head impacts for their respective sports. Although reducing head impacts is a logical and reasonable approach, proper instruction of blocking and tackling should still be utilized and practiced.
Test results throughout the study were similar to those found through previous research.\textsuperscript{42,43,57-62} Football postseason (12.8±5.7) BESS scores were similar to scores found by McCrea et al (12.73±7.6) and King et al (13.5±6.4).\textsuperscript{57,63} Women’s soccer was also similar to the research with their preseason scores (11.9±5.9). Both football pre and postseason SAC scores (27.5±2.2, 27.5±2.0) and women’s soccer pre and postseason SAC scores (27.5±1.9, 28.1±2) are close to McCrea et al (26.6±2.2) and Zimmer et al (27.17±2.9).\textsuperscript{58,59} Zimmer et al also found differences amongst gender, with female athletes (27.63) scoring higher than male athletes (26.97) overall and this was found through our research as well. Football KD scores (37.1±6.4, 34.1±5.4) and women’s soccer KD scores (39.2±5.1, 38.1±4.8) are similar to Galetta et al (38.6) who had a range of 36-40.2.\textsuperscript{40,41,64} ImPACT test scores were broken down into Verbal Memory, Visual Memory, Motor, and RT. Football postseason scores (88.6±8.3) were closest to the Iverson et al (88.7±9.5) and Schatz et al (89.3±8.2)\textsuperscript{50,60} scores, with women’s soccer preseason scores (90.4±10.5) similar as well. Visual Memory scores for football preseason (84.1±6.3) and postseason (86.1±11.3) are higher than Iverson et al (78.7±13.4) and Schatz et al (79.6±12.2).\textsuperscript{50,60} Football preseason Motor scores (40.5±5.6) are almost identical to the Iverson et al scores (40.5±7.6).\textsuperscript{60} Women’s soccer scores (0.53±0.04, 0.53±0.05) were almost identical to Iverson et al (0.54±0.09) and Schatz et al (0.54±0.06).\textsuperscript{50,60}

This study had several limitations. Football had limited participation and one player was lost due to injury. A large testing group could provide a more significant change for both group and time and results would also be more relatable to the general
athletic population. Additionally, participants utilized in this study were comprised of many different positions on the teams but some were not starting players. (Table 3.1) Two participants were football special team positions that do not usually sustain multiple impacts during practices or games. They did not participate in live practices and were only used during special team practice drills where they were not considered “live”. The effort from all participants during this study could also be a limitation. Tests utilized during this study need each participant’s full attention and effort. Testing points occurred at different points during the day, including morning and afternoon, and over the summer break when no mandatory workouts or practices for either team were being held. Participant effort could have been low during these times and may have an effect on the test results. Each test was only classified as a single task where each participant only had to complete one activity at a time. Research has shown that a dual task, or multiple tasks completed at the same time, show a higher variability between scores and could be a better measurement of neurocognitive and motor function.  

The head accelerometers used during this study have varying accuracy and validity across the literature. Jadischke found that head accelerations from HITS sensors were less accurate for specific head impacts, including direct facemask impacts, and a large range of inaccuracy for reported impacts. Beckwith found that HITS can accurately measure impact location but also over predicts severity of impacts. There is currently limited research on the Triax accelerometers, but they have proven to be valid through testing. However, further testing is still needed.
Compliance with the sensors was also a large limitation. Women’s soccer athletes would not wear their Triax headbands correctly or consistently throughout games and practices as compared to football HITS sensors that were embedded into their helmets. Some of the accelerations read by the Triax sensors could also not be used during this study because they were misread from another event, such as twirling the headbands around on an athlete’s finger or from hair hitting the sensor. The female athletes would wear their hair up in pony tails or buns that would inevitably hit the back of the headband and sensor, creating a false acceleration or impact reading. These events reached an acceleration greater than or equal to 10gs, creating a documented impact through the sensors that was not a true head impact. Up to 33% of the total acceleration readings had to be deleted because of this. However, the sensors are still being reviewed and analyzed through research with conflicting findings on the reliability and accuracy of the readings.\textsuperscript{29,32,62}

This is the first study to investigate pre and post-season neurological deficits over the course of an athletic season through an extensive concussion assessment battery while comparing collegiate football and women’s soccer. There were no associations herein between one season of head impacts for football and women’s soccer and short-term changes in neurologic function that would indicate impairment through clinical measures. Although football experienced a higher magnitude of overall head impacts than women’s soccer during the season, no differences were identified using standard concussion clinical testing assessment tools. The total
number of impacts, cumulative linear acceleration, and mean linear acceleration were not found to be significant predictive values for neurological impairment for either sport. Future research is needed to assess prolonged participation in male and female contact sports and the risk of neurological deficits after multiple seasons. One athletic season may not be long enough to determine any deficits through a concussion assessment battery.
REFERENCES


Appendix A

LITERATURE REVIEW

1. Concussion

1.1 Introduction

Concussions have been estimated to reach numbers between 1.6 and 3.8 million annually in the United States, accounting for 5-9% of all sports related injuries.\(^1\) There has been a steady increase in concussion rates that may be contributed to the increased awareness on head impacts and the need to self-report. There are many definitions for concussion; however, the most widely accepted comes from the most recent Zurich consensus statement, which states that a concussion is “a complex pathophysiological process affecting the brain, induced by traumatic biomechanical forces”.\(^68\) A concussion can occur as result of the head being struck or striking an object or the brain undergoing an acceleration or deceleration movement.\(^69\)

Concussions appear to be a recent health issue but, in reality, have been a medical issue for centuries. Rhazes was the first to use the term “concussion” in the modern sense around 900 AD.\(^70\) He referred to the injury as an abnormal physiologic state rather than a severe brain injury, changing the understanding of the injury completely.\(^70\) It wasn’t until the 16\(^{th}\) century when the “learned Doctor Read” noted the first list of signs and symptoms associated with concussion; these included ringing of the ears, falling, feeling dazed, loss of consciousness, seeing “stars” and feeling “giddy”.\(^70\) The clinical stages described by the “learned Doctor Read” are similar and
fairly accurate when compared to the list of signs and symptoms commonly associated with concussions today.

1.2 Metabolic Cascade

Concussion can be defined as a transient neurologic dysfunction occurring immediately after biomechanical injury to the brain followed by a complex cascade of ionic, metabolic, and physiologic events. Immediate changes occur through indiscriminant release of neurotransmitters and unchecked ionic fluxes occur. The most noted is the efflux of potassium and influx of calcium. These shifts lead to acute and subacute changes in cellular physiology of the brain. Following the influx, a glucose hypermetabolism occurs due to the overactive sodium-potassium pump and increased need for adenosine triphosphate (ATP). This creates a cellular energy crisis because the hypermetabolism occurs in an environment of diminished cerebral blood flow. Post-concussion vulnerability is common during this phase. A period of depressed metabolism and persistent increases in calcium may directly activate pathways leading to cell death. Increases in calcium may also impair mitochondrial oxidative metabolism and worsen the energy crisis.

1.3 Signs and Symptoms

Post-concussion symptoms are common and can include nausea, dizziness, headache, blurred vision, fatigue and sleep disturbance, poor memory, attention and executive functions, depression, irritability, anxiety and increased emotions. According to the 2014 National Athletic Trainers’ Association position statement on concussions, the following signs and symptoms are “red flags” that warrant immediate
referral to an emergency room: decreased or loss of level of consciousness, increased confusion and irritability, unequal pupil size, numbness in arms or legs, repeated vomiting, seizures, slurred speech and worsening headache.\textsuperscript{73}

Specific signs and symptoms can be linked to prolonged recovery when detected during initial evaluation. Dizziness at the time of injury was associated with prolonged return to play and recovery time.\textsuperscript{74} The main issue for athletic trainers is attempting to distinguish between dizziness and poor balance post-concussion. Loss of consciousness and amnesia were not found to be predictive of prolonged recovery because they were thought to be included within the normal post-concussion signs and symptoms and would resolve in a timely manner along with the other common signs and symptoms.\textsuperscript{74}

1.4 Short Term Effects

Immediate recovery time for high school and college athletes is directly related to self-reported symptomatology, postural control and cognitive recovery. It was found that high school athletes self-reported symptom recovery around 15 days post-concussion, while collegiate athletes state symptom recovery occurs around 6 days post-concussion.\textsuperscript{75} Early return to play, while symptoms persist, may predispose individuals to subsequent concussions and prolonged recovery time for concussion and neurocognitive symptom resolution.\textsuperscript{2} Guskiewicz et al found a “dose-response” with regards to a history of multiple concussions and risk of incident. Football players with a history of three or more concussions were three times more likely to sustain another concussion than those with no concussion history.\textsuperscript{5}
1.5 Concussion and Sport

Recent studies have found football to have the one of the highest overall rates of concussion (67.1/100,000 exposures) and highest annual reported concussions (3417) within all National Collegiate Athletic Association (NCAA) sports teams.\textsuperscript{18} Women’s Soccer, another sport known for head impacts, has the second highest number of annual reported concussions (1113) and a high overall rate of concussion (63.1/100,000 exposures).\textsuperscript{18} Soccer accounts for the highest number of head impacts and concussions among female athletes.\textsuperscript{23-25} Football has a high incidence of concussion likely because of the style of play, high number of impacts, and extent of sport participation.\textsuperscript{76} These factors create a higher risk of injury (5.54\%) and injury rate (3.74) for every athlete exposure, quantifying the risk every athlete has when participating in collegiate football.\textsuperscript{77}

1.6 Second Impact Syndrome

Second Impact Syndrome (SIS) can occur when an athlete, who has sustained an initial head injury, sustains a second head injury before the symptoms associated with the first impact have fully recovered.\textsuperscript{78} This second impact results in brain swelling that may lead to death. Although a serious injury, SIS is rarely reported.\textsuperscript{78} Experimental evidence has shown that there is a period of heightened susceptibility to a second concussion after the first initial injury.\textsuperscript{78} A rapid rise in cerebral glucose metabolism immediately after the first impact is followed by a period of depressed cerebral glucose metabolism, which could potentially be a biomarker for the susceptibility of a second impact.\textsuperscript{69,71} Resolution of clinical symptoms may not
coincide with the resolution of the metabolic imbalance within the brain, leaving the question of whether or not an individual is fully recovered when they experience the second impact.\textsuperscript{79}

1.7 Return to Play

Diagnosis is made through a clinical concussion battery that includes self-reporting, postural control, and cognitive evaluations, with resolution timing varying among individuals. It has been widely accepted, however, that a majority of young adults recover within 7-10 days with youth athletes taking longer.\textsuperscript{73,80} Once a diagnosis has been made, the return to play progression should not start until the athlete is symptom free. If symptoms return during any point of the progression, all activity should be stopped for that day and cannot restart until 24 hours later with the athlete asymptomatic. The progression would then restart from where the athlete stopped and continued as normal. Timing of recovery varies for each individual and may be lengthened or shortened based upon Athletic Trainer and team physician’s judgement.\textsuperscript{73}

Concussed athletes should return to play only after a team physician has cleared them for return to activity.\textsuperscript{73} The return to play protocol begins with avoiding any mental or physical exertion and instructing the athlete to continue eating and sleeping well.\textsuperscript{73} Normal return to play progressions include the following six day stages: 1) no activity, 2) light exercise, 3) sport specific activity without contact, 4) non-contact activity with other athletes, 5) unrestricted training or practice, and 6) return to full activity.\textsuperscript{73}
1.8 Long Term Effects

Long term effects are rarely associated with a single concussion. Symptoms are specific to each individual who sustains a concussion and long term effects may manifest years after the initial impact. Multiple concussions, however, have been associated with prolonged symptoms, recovery time, and increased risk for future concussions. A prospective cohort study in 2013 included almost 600 high school and collegiate athletes where multiple impacts and their long term effects were evaluated. It was found that athletes with three or more concussions took longer to recover after each subsequent concussion, lacking recovery in verbal memory and reaction time when compared to original baseline scores eight days post-concussion.

Chronic neurocognitive impairment (CNI) may present in post concussive syndrome or years later after an assumed resolution of concussion signs and symptoms. There is no known relationship between CNI and concussion history but has been shown in populations with a history of concussion and sub concussive impacts exposures.

Chronic traumatic encephalopathy (CTE) is defined as a progressive neurodegenerative syndrome caused by single, episodic, or repetitive blunt force impacts to the head and transfer of acceleration-deceleration forces to the brain. Severity of the disorder seems to correlate with the length of time engaged in the sport and number of traumatic injuries. Signs and symptoms can be insidious, manifested by deteriorations in attention, concentration and memory. Disorientation and
confusion, with occasional dizziness and headaches, are also common signs and symptoms. After progressive deterioration, additional symptoms like lack of insight, poor judgement and overt dementia can present as well.\textsuperscript{83} Prevention is sport specific and should focus on minimizing the frequency and severity of acute brain injuries, limiting exposures for a high risk athlete in a contact sport, and using protective equipment and padding appropriately and correctly.\textsuperscript{84}

### 1.9 Reporting Rates

There are multiple barriers that prevent reporting concussion symptoms among high school and collegiate athletes.\textsuperscript{85} It is estimated that 20-60\% of athletes do not report concussion symptoms.\textsuperscript{86,87} This could be due to inadequate athlete concussion knowledge and understanding.\textsuperscript{88,89} Within the high school population, both male and female athletes found it difficult to report concussion symptoms due to multiple factors; these included coach expectations, the specific sport environment, and fear of disappointing the team.\textsuperscript{85} Over half (66.4\%) of high school football players in Wisconsin stated they did not think their concussions were serious enough to report at the time of injury.\textsuperscript{87} It has been estimated that nearly half of collegiate student-athletes (49.7\%) suffered a potential concussion during their collegiate athletic careers and either never reported or failed to recognize them.\textsuperscript{90} Collegiate athletes’ reasoning for not reporting are similar to high school athletes, with the goal of continuing play and avoiding removal from the current and future games.\textsuperscript{90}
1.10 Gender Roles

Gender can play a large role in concussion outcomes and reporting rates among athletes. Female athletes have performed worse than male athletes on visual memory and reported more symptoms after a concussion. Female athletes also displayed greater changes from baseline cognitive performance than male athletes. Gender differences may be attributed to hormonal systems, cerebral organization, and musculature. Female athletes may be at a higher risk for concussion while also being more honest in reporting general injuries and symptoms.

2. Concussion Testing

2.1 SCAT3

The Sports Concussion Assessment Tool (SCAT) is an evaluative screen used post-concussion and in its third revised version. It was created to follow the domains of function that are most sensitive to the effects of concussions and include tests suitable for measuring those functions. The SCAT3 was created at the Fourth International Conference on Concussion in Sport held in Zurich, Switzerland in 2012. It includes initial assessment of injury severity using the Glasgow Coma Scale (GCS) before observing and documenting concussion signs. Additionally, the Maddocks scale, Standardized Assessment of Concussion and a modified, hard surface-only version of the Balance Error Scoring System are included within the SCAT3.

2.2 SAC

The Standardized Assessment of Concussion (SAC) is a set of questions targeted at cognitive assessment that provide a more objective and standardized
method of immediately assessment an athlete’s mental status post-injury. It is meant to be an addition to the other post-concussion tests utilized by medical professionals.\textsuperscript{92} The SAC questions are related to orientation, immediate memory, neurologic screening, concentration and delayed recall, and total scoring is out of 30 possible points.\textsuperscript{92} Orientation, Concentration, and Delayed Recall are out of 5 possible points and Immediate Memory is scored out of a possible 15 points.\textsuperscript{92} Average SAC scores for both high school and college populations were 26.6 ± 2.2.\textsuperscript{59} The SAC was found to have a high sensitivity (.80) at time of injury and high specificity (.89-.98) through the recovery period.\textsuperscript{93} McCrea et al found 95\% of injured subjects showed a drop in SAC total score by at least 1 point immediately post-concussion.\textsuperscript{92}

2.3 BESS

Balance disturbance is one of the most commonly reported post-concussion symptoms. The most frequently used clinical post-concussion scale for balance assessment is the Balance Error Scoring System (BESS).\textsuperscript{57} The BESS is a subjective test that involves three different stances (double limb stance, single limb stance and tandem stance) on two surfaces (firm and foam) with each stance lasting 20 seconds.\textsuperscript{94} Scoring is based off of errors counted by the test administrator and include lifting hands off the iliac crest, opening the eyes, stepping, stumbling or falling, moving the hip into more than 30 degrees of flexion or abduction, lifting the forefoot or heel and remaining out of the testing position for more than five seconds.\textsuperscript{94} It is useful for sideline application during games or practices, cost effective and requires less training for test administrators.\textsuperscript{95}
The BESS was found to have moderate sensitivity (.34) and high specificity (.91-.97).\textsuperscript{93} Finnoff et al looked into the intrarater and interrater reliability of the BESS to assess minimum detectable change for scores. The study showed that both intrarater reliability (ICC 0.50 – 0.88) and interrater reliability (ICC 0.44 – 0.83) ranged from moderate to good reliability with total BESS score intrarater (ICC 0.74) and interrater (ICC 0.57) reliability showing similar results.\textsuperscript{39}

Balance tests are generally considered either subjective or objective; Subjective tests involve examiners using qualitative criteria and objective tests utilize the analysis of quantitative data from force plates and motion analysis equipment.\textsuperscript{95} Recently, the BESS has become both subjective and objective with the use of force plates and balance sensors. King et al conducted a study using 13 subjects who wore an inertial sensor around their waist during BESS testing. With just subjective tester scoring, only 3 of the 13 participants were found to have abnormal balance when compared to baseline. After the addition of the sensor, data showed that 7 of the 13 participants were labeled as abnormal, a group that could have been returned to play prematurely without the use of the sensor.\textsuperscript{57}

2.4 King-Devick Test

The King-Devick Test is a measurement of speed for rapid number naming and reading.\textsuperscript{96} Research has shown that poor oculomotor function has been an identifier for dysfunction in areas of the brain post-concussion.\textsuperscript{97} The test involves reading aloud a series of single-digit numbers from left to right on three test cards. The K-D test includes one practice card and three test cards with standardized instructions used
throughout the test session that requires less than two minutes. Subjects are instructed
to read the numbers on each card from left to right as quickly as possible without
making any errors. The K-D time score is comprised of the sum of the three test card
time scores with number of errors made in reading the test cards recorded.\textsuperscript{40,64}

2.5 ImPACT Test

The Immediate Post-Concussion Assessment and Cognitive Test (ImPACT) is
a computer-based test battery used for assessing neurocognitive function and
concussion symptoms. It is the most widely used computerized testing program in the
sports setting.\textsuperscript{98} The ImPACT test focuses on three major categories within the test;
these include demographics, concussion symptoms and neurocognitive tests. Within
the three test categories, six modules evaluate attentional processes, verbal recognition
memory, visual working memory, visual processing speed, reaction time, numerical
sequencing ability and learning.\textsuperscript{60} Combined test sensitivity is 81.9\% and specificity is
89.4\%.\textsuperscript{50}

2.6 Ruler Drop Test

The Ruler Drop Test is a simple measurement of reaction time that first
originated in schools when students were asked to catch a vertical ruler when suddenly
and randomly released.\textsuperscript{44} The apparatus used is a 1.3m dowel rod marked in 0.5cm
increments and embedded into a weighted rubber disc 7.5cm wide and weighing 256g.
The weighted disc standardizes the distance the rod falls after release and helps to
ensure the rod will fall nearly vertical when suspended.\textsuperscript{44} Participants complete ten
total trials with both dominant and non-dominant hands. There are normally two
practice trials before eight test trials for each hand.44

2.7 Practice Effect

Repeating specific tests post-concussion is common but now creates a potential
practice effect that may skew future data collection. This creates a difficult job for
researchers that need to identify performance improvements from true neurologic
recovery instead of learning or practice effects.55 Previous findings within literature
have shown practice effects, or improvements in performance, for neuropsychological
test batteries.99,100 Practice effects have also been found in postural stability
assessments, specifically BESS.55,101,102

3. Accelerometers

3.1 Background

The use of accelerometers has been studied and modified over the last
decade.103 Head velocity and acceleration are important variables used to assess the
capability of the equilibrium because they represent actual inputs for the vestibular
system.104,105 Early accelerometer prototypes measured specific head impact exposure
details but were difficult to administer for both athlete and tester.106-108 Accelerometers
today are primarily associated with football and measuring head impacts during
practices and games; studies have recreated specific game impacts and injuries using
accelerometers within labs.109 Measuring impacts and tracking the location of head
impacts has also become a popular topic within collegiate football.19,110
3.2 Head Impact Telemetry System

The Head Impact Telemetry System (HITS) is comprised of helmet mounted accelerometers used to determine the linear and angular acceleration of the head during motion and contact.\textsuperscript{66} The accelerometers are single axis and spring mounted that keep constant contact with the head at all times. They are embedded into the helmets and used to track the frequency, magnitude and location of impacts for each individual athlete. Real-time data from impacts are sent to a signal receiver and sideline computer system. Data are collected for 40 ms when any accelerometer detects an acceleration that exceeds 10 g. Each helmet unit can store up to 33 impacts on downloadable memory if wireless communication is not present.\textsuperscript{31}

Studies focusing on the biomechanics associated with brain injury found that there are two main injury modes: linear and rotational acceleration.\textsuperscript{111} Linear acceleration based injury is thought to associate with transient intracranial pressure gradient while rotational acceleration results from a strain response.\textsuperscript{111} Through extensive research, Rowson and Duma calculated that the top 50\% of sub-concussive impacts had a peak linear acceleration greater than 19 g while the top 25\% sub-concussive impacts had a peak linear acceleration greater than 31 g.\textsuperscript{111} The HITS has been validated through previous studies and laboratory testing.\textsuperscript{31}

3.3 Triax Accelerometers

The Triax head accelerometers measure head impacts sustained during play in real time for non-helmeted sports.\textsuperscript{32} The specific device is called a Smart Impact Monitor (SIM) and comprised of a high-g 3-axis accelerometer, low-g 3-axis
accelerometer, rechargeable lithium ion battery, and 900 MHz radio.\textsuperscript{32} It weighs 11.5 grams and is placed in a custom headband that is worn on the athlete’s head above the nuchal line.\textsuperscript{32} All information is stored on the Triax’s cloud server when internet is not available and can be viewed in real time when connected through USB to a sideline computer.\textsuperscript{32} The SIM can measure g-force levels from 3-150gs and rotational impact information. However, the headband has a threshold of 16g and will only download impacts greater than or equal to that threshold.\textsuperscript{32} Once an impact is recognized, 10ms before and 52ms post-impact will be recorded and transmitted to a sideline computer that is within 150 yards. If players are out of range, the headbands can store up to 140 impacts until they are returned to within range.\textsuperscript{32}

4. Testing Battery

4.1 Effectiveness

Multidimensional concussion assessment test batteries are recommended for the evaluation, diagnosis, and management of sport related concussions and not just the reliance on one singular test.\textsuperscript{15-17} When performed individually, a single measure in any domain was no more 60\% sensitive to concussion; the testing battery as a whole was over 90\% sensitive to concussion.\textsuperscript{15} Utilizing a battery instead of each singular test could reduce the risk of missing a concussion and returning an athlete to play sooner than expected.

4.2 Common Tests

A multidimensional concussion assessment battery should include symptom, neurocognitive, and balance measures for a complete assessment.\textsuperscript{15} Athletic trainers
follow specific protocols that require different measures for the evaluation and management of concussions. A poll across Division I NCAA athletic trainers found specific test were used more frequently than others for specific concussion testing domains. A large portion (73.9%) of athletic trainers reported using BESS as the most common balance baseline test, with SAC (72.2%) as the most common cognitive baseline test. The ImPACT test (88.8%) was the most popular neurocognitive test. Overall, about 70% of all Division I NCAA athletic trainers used at least three assessment techniques within their concussion testing batteries. These results, however, were not seen in NCAA Division II and III athletic trainer assessment batteries. Multifaceted baseline concussion testing was endorsed by less than half (40-1-43.1%) of athletic trainers who responded to specific study. It can be assumed that factors leading to these results include fewer athletic trainers on staff and less resources at this level of competition.

5. Repetitive Head Impacts

Repetitive head impacts are a cranial impact that does not result in known or diagnosed concussion on clinical grounds. Symptoms may not develop and there are no outward or visible signs of neurological dysfunction. The greatest effect of repetitive head impacts impacts to the head occur through repetitive occurrences with cumulative exposures. A “slosh” phenomenon also exists when a rapid acceleration-deceleration of the body or torso occurs when the brain is free to move within the cranium. It is estimated that collegiate football players sustain an average of three subconcussive blows to the head a game. The main focus surrounding repetitive head
impacts impacts is whether or not sustaining multiple repeated impacts over the course of a season effects post-season testing and cognitive function.

6. Pre-Post Season Testing

6.1 Clinical Findings

Many studies have hypothesized that a large number of subconcussive impacts, or repeated head impacts, over the course of a sport season could create a decrease in neurocognitive function. Studies that followed football players through a high school and college season could not find a direct correlation between decreased neurocognitive scores and increased number of head impacts.\textsuperscript{14,51,112} There may be a subgroup, however, that presents with learning and memory deficits after the course of one athletic season.\textsuperscript{11,113} These groups represent the need to continue post season testing for further education on cognitive deficits and repeated head impacts.

One specific study combined a multifaceted concussion assessment battery with pre and post season testing for middle school football players. Although they experienced impacts similar to those at the high school and collegiate level, there were no immediate short term deficits after a full athletic season.\textsuperscript{13}

6.2 Test Effect Factors

Repeated head impacts are not the sole factor that could create neurocognitive deficits after the course of one athletic season. Multiple other factors can contribute to the decline in performance during post-season concussion assessment testing. Sleep, and sleep duration, are taken into account when performing cognitive assessments. Sleep related symptoms and reduced sleep duration negatively affected neurocognitive
performance. These symptoms may include physical, emotional and cognitive related complaints.\textsuperscript{114} Athletes who reported reduced sleep performed worse on multiple concussion assessments, including ImPACT, reaction time, and visual motor speed.\textsuperscript{115,116} Knowledge of an athlete’s sleeping patterns, or even the amount of sleep they had the night before, could give better insight to test scores and neurocognitive performance.

Previous studies have shown that maximal exercise and fatigue have a limited effect on cognitive function when neuropsychological test batteries are administered post activity.\textsuperscript{117} Postural control is also temporarily effected by fatigue, with a decrease in overall control.\textsuperscript{118} Dehydration is also associated with fatigue and can create temporary deficits during concussion assessments. Although no specific differences were found between groups during one study, dehydrated athletes experienced deterioration in visual memory and fatigue measures, along with a higher number and severity of symptoms.\textsuperscript{119} Similar to knowing an athlete’s sleep patterns, having a better knowledge about their fatigue levels could provide a better testing session with more accurate data. Avoiding baseline testing or assessments immediately after activity could potentially avoid the risk of fatigue and dehydration from skewing results.

Attention Deficit Disorder (ADD) and Attention-Deficit/Hyperactive Disorder (ADHD) have been linked with traumatic brain injuries and concussions in previous literature.\textsuperscript{120} ADHD is a childhood onset neurodevelopmental and persistent disorder associated with impulsive and risk taking behavior.\textsuperscript{121,122} Athletes with ADHD present
with slower verbal memory, visual memory, and visual motor processing speed scores during baseline ImPACT neurocognitive testing. These athletes also had significantly higher reaction time, impulse control, and symptom scores when compared to athletes without ADHD. Overall, this specific athlete population has a lower baseline score on neurocognitive baseline testing than other athletes without ADD/ADHD and could benefit from having their own set of normative baseline measures. Knowing whether or not athletes have these attention-deficit disorders will provide a better understanding to baseline and post-injury concussion testing.

7. Conclusion

Understanding the role of repeated head impacts, or subconcussive impacts, is very important for athletes and athletic trainers involved in high impact and contact sports. Football and soccer are two sports with a large amount of head impacts on a daily basis as part of the general game play. Through pre and post season testing, athletic trainers can quantify and compare test results to baseline measurements to examine any deficits or changes that may have occurred. If athletes have a decrease in neurocognitive function or concussion assessments after a full athletic season without any diagnosed concussions, repeated head impacts may have a role in these deficits. Although the literature does not fully support this idea, there are small groups within studies that do support these ideas and call for further investigation.

Utilizing a comprehensive testing battery provides a stronger testing baseline to use with a higher sensitivity than singular tests on their own. The current literature suggests using a testing battery to evaluate and manage concussions. Testing batteries
encompass a wide range of concussion testing aspects and provide a well-rounded assessment. It should be noted, however, that many factors could create deficits within the battery that are similar to concussion symptoms. Sleep, attention deficit disorders, fatigue, and dehydration can all effect concussion negatively. Even at baseline of a normal athlete, these factors could produce results similar to those who have a concussion. Athletic trainers should always be aware of their athletes’ schedules and the complications these factors may create.

An overall concussion battery that quantifies head impacts is an ideal pre and post season test that could give a vast amount of information to researchers on the consequences an athlete may endure over the course of a full season.
References


Appendix B

IRB APPROVAL LETTER
DATE: March 17, 2016

TO: Thomas Kaminski
FROM: University of Delaware IRB

STUDY TITLE: [740790-3] NCAA/DoD Grand Alliance: Concussion Assessment, Research and Education (CARE) Consortium – Longitudinal Clinical Study Core

SUBMISSION TYPE: Continuing Review/Progress Report

ACTION: APPROVED
APPROVALDATE: March 17, 2016
EXPIRATIONDATE: April 14, 2017
REVIEW TYPE: Expedited Review

REVIEW CATEGORY: Expedited review category # (9)

Thank you for your submission of Continuing Review/Progress Report materials for this research study. The University of Delaware IRB has APPROVED your submission. This approval is based on an appropriate risk/benefit ratio and a study design wherein the risks have been minimized. All research must be conducted in accordance with this approved submission.

This submission has received Expedited Review based on the applicable federal regulation.

Please remember that informed consent is a process beginning with a description of the study and insurance of participant understanding followed by a signed consent form. Informed consent must continue throughout the study via a dialogue between the researcher and research participant. Federal regulations require each participant receive a copy of the signed consent document.

Please note that any revision to previously approved materials must be approved by this office prior to initiation. Please use the appropriate revision forms for this procedure.

All SERIOUS and UNEXPECTED adverse events must be reported to this office. Please use the appropriate adverse event forms for this procedure. All sponsor reporting requirements should also be followed.

Please report all NON-COMPLIANCE issues or COMPLAINTS regarding this study to this office.

Please note that all research records must be retained for a minimum of three years.
Based on the risks, this project requires Continuing Review by this office on an annual basis. Please use the appropriate renewal forms for this procedure.

If you have any questions, please contact Nicole Farnese-McFarlane at (302) 831-1119 or nicolefm@udel.edu. Please include your study title and reference number in all correspondence with this office.