DIFFERENCES IN HEAD ACCELERATION ACROSS IMPACT TYPE, PLAYER POSITION, AND PLAYING SCENARIO IN COLLEGIATE WOMEN’S SOCCER ATHLETES

by

Lindsey C Lamond

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

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ABSTRACT

Women’s soccer athletes are exposed to 2.7-6.9 impacts per competitive game, leading to a large number of impacts over the course of one’s career. The long-term effects of these repetitive impacts have been debated with some studies reporting neuropsychological and structural injury and others reporting no changes. In order to understand these impacts, head acceleration has been used to quantify impacts on the field in sports such as football and ice hockey. The purpose of this study is to quantify and compare head accelerations during women’s soccer by player position, impact type, and playing scenario, games and practices. Twenty-four NCAA Division-I women’s soccer players were equipped with Smart Impact Monitors (SIMs), which were worn during all practices and games. The SIMs were secured to the head and positioned just below the inion using a custom headband. Real-time accelerations were transmitted wirelessly to a computer on the sidelines. Visual, on-field monitoring of games and practices allowed for the classification (type) of impact. Results indicate significant differences in peak linear accelerations exist between player position, type of impact, and playing environment. Information gathered from this investigation is important to identify athletes at risk of injury due to the various factors associated with head impacts.
Chapter 1

INTRODUCTION

It has been reported that a collegiate soccer athlete is exposed to between 2.7 and 6.9 head impacts, on average, during each competitive game. In the game of soccer, an athlete may use his/her head to pass, shot, and control the ball, which can lead to a number of repetitive head impacts. In addition to purposeful soccer heading, unanticipated head impacts, such as head-to-head contact may occur, and these impacts are often considered more serious in nature in that they are more likely to result in injury. The effects of these repetitive impacts has been debated with some authors reporting a decline in performance on neuropsychological tests as well as structural changes due to repetitive head impacts received while playing soccer. Others report no neuropsychological or structural deficits from these repetitive head impacts, leaving the effects of these impacts still unknown. Therefore, the first step in understanding these impacts is to quantifying the head impacts that occur during soccer. This will allow for further understanding of the potential risk factors associated with repetitive head impacts.

Several studies have quantified head acceleration during purposeful soccer heading. However, many of these studies were limited due to a lab testing environment which utilized ball speeds well below those thought to occur during competition on the field. One study used higher ball speeds (30mph, 40mph, and 50mph) to study ball-to-head impacts, more similar to what may be observed
during practice and games, and reported higher head accelerations than studies using slower ball speeds.\textsuperscript{11} Moreover, these studies were limited due to the focus on only ball-to-head contacts.\textsuperscript{11,35,42} In an attempt to better understand the head impacts that occur during the game of soccer, laboratory reenactments of head-to-head and upper extremity-to-head contacts were used to mimic on-field head impacts.\textsuperscript{54} The head accelerations during these impacts were greater than previously reported with ball-to-head contacts.\textsuperscript{54} Still, these represented controlled head impact scenarios, but soccer is not played in a controlled laboratory environment.

Due to advancement of accelerometer technology, observing on-field, real-time head accelerations in soccer is now possible and broadens the scope of soccer head impact research. This technology has allowed for comparison of head impact magnitude across impact type, with unanticipated or “non-header” impacts resulting in higher head acceleration than “header” impacts.\textsuperscript{16} However, these results were observed with a small sample size of youth soccer athletes during six scrimmages, and therefore the results may not be applicable across all levels of soccer play.

Head acceleration may not only be influenced by type of impact, but also by player position. Differences in head acceleration based upon player position have been identified in sports such as football\textsuperscript{4,7–9,32} and ice hockey.\textsuperscript{33,38} While differences in head accelerations across various player positions have not been reported in soccer, head injury rates by position have been observed with more head injuries being sustained by defenders\textsuperscript{14} and goalkeepers when compared with other field positions.\textsuperscript{2,10,26} Therefore, this may indicate that these athletes are exposed to a higher number and magnitude of impacts than their teammates.
Furthermore, playing environment influences head accelerations with games resulting in higher head accelerations as observed in football\(^7\)\(^-\)\(^9\)\(^,\)\(^{39}\) and ice hockey\(^3\)\(^,\)\(^{33}\)\(^,\)\(^{53}\). Additionally, one on-field soccer study observed higher head accelerations and a greater number of impacts on the field during games than during practices.\(^{31}\) This could be due to the inherent competitive nature in games. Furthermore, especially in soccer, due to the more controlled environment of practice, there may be fewer opportunities to head the ball when compared to games.

Two studies have incorporated head accelerometer technology during on-field play in women’s youth, high school, and collegiate soccer.\(^6\)\(^,\)\(^{16}\)\(^,\)\(^{31}\)\(^,\)\(^{36}\) However, there is still missing information regarding the effect of the type of impact and playing position on the observed head acceleration. Therefore, the purpose of this study was to investigate real-time head acceleration in collegiate women’s soccer across type of impact, athlete position, and game or practice scenario. On-field head accelerations were observed during practices and games in collegiate women’s soccer and were categorized and compared by impact type as well as player position; allowing for a more comprehensive description of the impacts that occur on the soccer field during play.
Chapter 2

METHODS

2.1 Study Participants

Twenty-four NCAA Division-I women’s soccer student-athletes (age=19.7±1.2 years; height= 168.3±4.2 cm; mass=62±4.5 kg) participated in this study. All participants were recruited and gave informed consent (IRB #500033-2) prior to the start of their Fall 2015 season. Our cohort represented all playing positions (forwards (6), defenders (3), midfielders (11), and goalkeeper (3)). Athletes were excluded from a particular day’s data collection if they did not wear their headband or took the headband off during play. Additionally, one student-athletes was excluded due to season ending injury.

2.2 Smart Impact Monitors

A triaxial accelerometer, the Smart Impact Monitor (SIM) (Triax Technologies, Norwalk, CT), used in this study is able to measure head accelerations from 3-150g. Internal validation of the SIM was performed at the Neurotrauma Impact Science Laboratory at the University of Ottawa. A NOCSAE headform, instrumented with 9 single-axis accelerometers at the center of gravity of the headform, and a SIM, secured to the head by a custom headband placed below the inion, was impacted with a pendulum system at eleven different impact locations and across three energy levels, 30g, 50g, and 80g, for a total of 87 impacts. Data were collected from the 9 single-axis accelerometers and the SIM at 1000 Hz. The peak
resultant acceleration for each impact waveform was compared with that of the instrumented headform. Results indicate that the SIM can accurately report peak linear acceleration (PLA) ($r^2=0.84$) and peak rotational acceleration (PRA) ($r^2=0.78$).\textsuperscript{49}

2.3 Instrumentation

Each athlete was assigned a SIM, as well as a custom headband (Figure 1) with a pocket to fit the SIM. The SIM, once in the headband, was positioned at the back of the athlete’s head above the nuchal line, below the occipital protuberance (Figure 1). Student-athletes were instructed on how to properly place the sensor in the headband and position it on the head at the beginning of the season. Placement of each headband was then monitored carefully throughout the season by the research team. Student-athletes kept their headbands throughout the season, and were responsible for cleaning and care. The SIMs were kept by the researchers and were handed out at the beginning of each practice/game. SIMs were recharged on a weekly basis.

Figure 1 Smart Impact Monitor with specially designed headband and placement of headband on the head
The SIMs had a threshold of 10g, which is consistent with previous head impacts biomechanics research. During competitive soccer play, head accelerations above the 10g threshold were wirelessly transmitted to a sideline computer via a USB access point. This was done for all impacts that occurred within 150 meters of the computer. If athletes were outside this range, the SIM stored up to 140 impacts, which were downloaded once back in range. Data from the SIMs were processed to remove any impacts recorded prior to placement or after removal of the SIM.

All impacts were visually observed on the field and also manually recorded by researchers on the sideline using a simple tally during every practice and game. In this study, impacts were classified by athlete and impact type, which had nine possible categories (Table 1): clear, pass, shot, unintentional deflection, head-to-head, upper extremity-to-head, lower extremity-to-head, head-to-ground, and body contact. Intra-rater and inter-rater reliability of real time classification were calculated using game film from 5 games. Results revealed poor inter-rater (0.3) agreement and moderate intra-rater agreement (0.6).
Table 1 Definitions for Impact Type

<table>
<thead>
<tr>
<th>Type of Contact</th>
<th>Type of Impact</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Clear</td>
<td>A deflection of the ball with no goal of gaining control, simply to get the ball out of the area. Used mostly by defensive and midfield players on the defensive side of the field.</td>
<td></td>
</tr>
<tr>
<td>Pass</td>
<td>Trying to gain control of the ball through heading, either by trapping or passing to a teammate. Used mostly by midfielders and forwards in the upper defensive and offensive sides of the field.</td>
<td></td>
</tr>
<tr>
<td>Header</td>
<td>Shot</td>
<td>Heading the ball with the intention of scoring a goal. Used mostly by forwards and occurs within the goal box on the offensive side of the field.</td>
</tr>
<tr>
<td></td>
<td>Unintentional Deflection</td>
<td>A head impact with the ball that was unexpected.</td>
</tr>
<tr>
<td></td>
<td>Head-to-Head</td>
<td>A collision with another's head (opponent, official, or teammate).</td>
</tr>
<tr>
<td>Non-Header</td>
<td>Upper Extremity-to-Head</td>
<td>When a player's head is hit by another's hand, wrist, forearm, elbow, upper arm, or shoulder (opponent, official, or teammate).</td>
</tr>
<tr>
<td></td>
<td>Lower extremity-to-Head</td>
<td>When a player's head is hit by another's foot, leg, knee, thigh, or hip (opponent, official, or teammate).</td>
</tr>
<tr>
<td></td>
<td>Head to Ground</td>
<td>When a player's head comes in contact with the ground.</td>
</tr>
<tr>
<td>Body Contact</td>
<td>When linear acceleration of the head is generated through force transmission from a body contact to the head (i.e. a player falling to the ground, two players colliding in the air, or a goalie laying out for a save).</td>
<td></td>
</tr>
</tbody>
</table>

At the end of each practice or game, all impacts were downloaded, categorized, and labeled. Data were organized to remove all impacts that occurred prior to and after the removal of the SIM. Additionally, all impacts occurring before the start and after the end of the game or practice were removed. Each impact was then sorted by athlete.
position, type of impact, and playing scenario, game or practice. Additionally athlete participation was monitored with one athlete-exposure representing participation in one athletic session (game or practice).

2.4 Data Analysis

Data analysis included all impacts that exceeded the 10g threshold during games and practices, which were also visually verified by researchers. Descriptive statistics of linear accelerations including the median, 75th quartile, and 25th quartile values were calculated for game, practices, and season according to the recommendations of King et al.\textsuperscript{22}

Data were analyzed using a multilevel linear model. Multilevel models typically include both random-effects and fixed-effects. They are recognized as being the best method of analysis when data are nested.\textsuperscript{43} One way data become nested is hierarchically. In the current study, the number of head accelerations varied by athlete, and therefore, was hierarchically nested within athletes. When nesting occurs, data become homogenous. Researchers need account for the homogeneity, otherwise, standard errors will become too small, and in turn, the results will appear to be larger (and more statistically significant) than their correct values.\textsuperscript{17}

The dependent variable was linear accelerations and the number of accelerations served as a random-effect (intercept). All fixed-effects predictors were on the nominal level of measurement and were dummy coded. The fixed-effect predictors included type of header impact: pass, clear, shot with body contact coded as the base variable, non-header impact (header to ground [HG], head to head [HH], unintentional deflection [UD], upper extremity to head [UEH], lower extremity to head [LH] with body contact coded as the base), field position (goalie, forward,
defense with midfield coded as the base) and game versus practice with practice coded as the base. Regression coefficients were modeled using maximum likelihood estimation with variance components as the variance-covariance error structure. All reported $p$-values were two-sided ($p=0.05$).
Chapter 3

RESULTS

Of the 23 student-athletes who completed the study all playing positions were represented including 3 goalkeepers, 3 defenders, 11 midfielders, and 6 forwards. There were 1,449 possible athletes exposures across the season consisting of 20 games and 43 practices. 488 of these exposures were excluded due to athletes not participating (practice or game) or not wearing/removing their headband.

The SIMs recorded 3,177 impacts, which were also visually verified by researchers and included in the final data analysis. Over the course of the season the median impact was 12.52g (range 10-160.6g) and the 25th to 75th interquartile range was 10.97-16.28g. The season resulted in 3.30 impacts per athlete-exposure. Games resulted in 1,596 impacts recorded by the SIMs, with a median impact of 12.57g (range 10-160.6g) and the 25th to 75th interquartile range of 11.82-13.62g (Figure 2). Games resulted in 6.03 impacts per athlete-exposure. Practices resulted in 1,581 impacts recorded by the SIMs, with a median impact of 12.45g (range 10-102.23g) and 25th to 75th interquartile range of 11.08-15.09g (Figure 2). Practices resulted in 2.28 impacts per athlete-exposure. Descriptive statistics including means, median, as well as 95% confidence intervals are presented in Table 2.
3.1 Playing Scenario

The multilevel analysis resulted in a significant ($F_{1,1695.49}=8.08$, $p=0.005$) difference in the head accelerations that occur in games and practices, with games (mean=17.77g) resulting in a significantly higher average linear accelerations than practices (mean=14.58g) ($b=1.17$, $p=0.005$) (Table 2).

3.2 Type of Impact

Comparisons of linear acceleration by type of impact are shown in Figure 3. There was a significant difference when comparing linear accelerations by type of impact (Table 2). Compared to body contacts, passes ($b=12.42$, $p=0.001$), clears ($b=17.24$, $p=0.001$), shots ($b=20.19$, $p=0.001$), head-to-ground ($b=13.98$, $p=0.001$), head-to-head ($b=35.94$, $p=0.001$), unintentional deflections ($b=23.55$, $p=0.001$), and upper extremity-to-head ($b=25.45$, $p=0.001$) impacts all resulted in significantly higher linear accelerations. There was no significant difference between lower extremity-to-head impacts ($b=-0.06$, $p=0.994$) and body contacts.

3.3 Player Position

Means and medians by player position are presented in Table 2 and comparison of linear acceleration by player position are presented in Figure 4. There was no significant difference between forwards ($b=-0.34$, $p=0.715$) and defenders ($b=-0.47$, $p=0.668$) compared to midfielders. Goalkeepers ($b=2.15$, $p=0.001$) differed significantly from midfielders.
Figure 2 Box-and-Whisker Plot of Linear Acceleration by Playing Scenario. Whisker height represents range in linear acceleration. Box height represents 25th to 75th interquartile range. Mean represented by divide between quartiles.
Figure 3 Box-and-Whisker Plot of Linear Acceleration by Impact Type. Whisker height represents range in linear acceleration. Box height represents 25th to 75th interquartile range. Mean represented by divide between quartiles.
Figure 4 Box-and-Whisker Plot of Linear Acceleration by Player Position. Whisker height represents range in linear acceleration. Box height represents 25th to 75th interquartile range. Mean represented by divide between quartiles.
Table 2 Means, Medians, and Results of Fixed Effects from Multilevel Analysis

<table>
<thead>
<tr>
<th>Predictor</th>
<th>Value or Coding</th>
<th>Count</th>
<th>Median</th>
<th>Mean</th>
<th>SD</th>
<th>Table 1</th>
<th>Linear Acceleration</th>
<th>95% Confidence Interval</th>
<th>Beta (SE)</th>
<th>p</th>
</tr>
</thead>
<tbody>
<tr>
<td>Intercept</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Header Impact</td>
<td>Pass</td>
<td>452</td>
<td>20.76</td>
<td>26.04</td>
<td>15.51</td>
<td>12.42</td>
<td>(0.46)</td>
<td>11.52</td>
<td>13.33</td>
<td>0.001</td>
</tr>
<tr>
<td></td>
<td>Clear</td>
<td>105</td>
<td>29.82</td>
<td>31.43</td>
<td>13.20</td>
<td>17.24</td>
<td>(0.89)</td>
<td>15.49</td>
<td>18.98</td>
<td>0.001</td>
</tr>
<tr>
<td></td>
<td>Shot</td>
<td>40</td>
<td>29.82</td>
<td>28.81</td>
<td>12.76</td>
<td>20.19</td>
<td>(1.43)</td>
<td>17.39</td>
<td>22.98</td>
<td>0.001</td>
</tr>
<tr>
<td>Non-Header Impact</td>
<td>Head-to-Ground</td>
<td>8</td>
<td>22.53</td>
<td>27.35</td>
<td>14.69</td>
<td>13.98</td>
<td>(2.99)</td>
<td>8.09</td>
<td>19.86</td>
<td>0.001</td>
</tr>
<tr>
<td></td>
<td>Head-to-Head</td>
<td>13</td>
<td>35.34</td>
<td>51.26</td>
<td>36.61</td>
<td>35.94</td>
<td>(2.37)</td>
<td>31.30</td>
<td>40.58</td>
<td>0.001</td>
</tr>
<tr>
<td></td>
<td>Unintentional Deflection</td>
<td>26</td>
<td>22.74</td>
<td>37.05</td>
<td>33.48</td>
<td>23.55</td>
<td>(1.74)</td>
<td>20.14</td>
<td>26.96</td>
<td>0.001</td>
</tr>
<tr>
<td></td>
<td>Lower Extremity-to-head</td>
<td>1</td>
<td>13.37</td>
<td>13.37</td>
<td>13.37</td>
<td>-0.06</td>
<td>(5.98)</td>
<td>-16.64</td>
<td>16.51</td>
<td>0.994</td>
</tr>
<tr>
<td></td>
<td>Body Contact</td>
<td>2530</td>
<td>11.85</td>
<td>13.10</td>
<td>4.62</td>
<td>-</td>
<td>(Ref)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Position</td>
<td>Goalkeeper (N=3)</td>
<td>887</td>
<td>12.72</td>
<td>13.74</td>
<td>3.99</td>
<td>2.15</td>
<td>(0.66)</td>
<td>0.85</td>
<td>3.46</td>
<td>0.001</td>
</tr>
<tr>
<td></td>
<td>Forward (N=6)</td>
<td>475</td>
<td>11.72</td>
<td>14.92</td>
<td>9.18</td>
<td>-0.34</td>
<td>(0.91)</td>
<td>-2.21</td>
<td>1.53</td>
<td>0.715</td>
</tr>
<tr>
<td></td>
<td>Defense (N=3)</td>
<td>973</td>
<td>12.3</td>
<td>16.51</td>
<td>11.30</td>
<td>-0.47</td>
<td>(1.07)</td>
<td>-2.72</td>
<td>1.78</td>
<td>0.668</td>
</tr>
<tr>
<td></td>
<td>Midfield (N=11)</td>
<td>842</td>
<td>13.11</td>
<td>19.09</td>
<td>14.27</td>
<td>-</td>
<td>(Ref)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Playing Scenario</td>
<td>Game (N=20)</td>
<td>1596</td>
<td>12.57</td>
<td>17.77</td>
<td>12.99</td>
<td>1.17</td>
<td>(0.41)</td>
<td>0.36</td>
<td>1.99</td>
<td>.005</td>
</tr>
<tr>
<td></td>
<td>Practice (N=43)</td>
<td>1581</td>
<td>12.45</td>
<td>14.58</td>
<td>7.37</td>
<td>-</td>
<td>(Ref)</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

N = 3,177 impacts.

1 \( Beta = \) the unstandardized beta coefficient, SE = the standard error of the unstandardized coefficient.
Chapter 4
DISCUSSION

The purpose of this study was to describe the linear head accelerations that occur on the field during collegiate women’s soccer games and practices and to determine differences in linear acceleration based upon player position, type of impact, and playing scenario. Results of this study showed differences in linear head acceleration due to playing scenario, with games resulting in higher linear head accelerations. Player position was also shown to have an effect on linear head acceleration with midfielders having the highest linear accelerations. Finally, non-header impacts such as head-to-head, head-to-ground, upper extremity-to-head, and unintentional deflections resulted in the highest linear head accelerations. The results of this study expand upon the current head acceleration research in sports such as football and ice hockey, as well as add to the four current studies that have quantified head accelerations on the field during soccer\(^\text{6,16,31,36}\)

Playing scenario, games versus practices, resulted in differences in head accelerations (games = 17.77g, practices = 14.58g), which has also been observed in ice hockey\(^\text{3,33,53}\), football\(^\text{7–9,39}\) and soccer\(^\text{31}\). In ice hockey, this observed difference in mean linear acceleration is small and not statistically significant (games = 18.3g, practices = 18.1g).\(^\text{33}\) Similarly, in football, the observed difference between mean linear acceleration was very small (games = 20.2–28.2g, practices = 20.0–28.8g).\(^\text{9,39}\) In soccer, McCuen et al. observed significantly higher linear accelerations during collegiate women’s soccer games (41.2g) than practices (37.7g).\(^\text{31}\) The linear
accelerations presented by McCuen et al. are higher than what we reported because McCuen et al. employed a higher threshold of 20g compared to our 10g threshold. Together, these studies suggest that the more competitive nature of games allows for higher head accelerations in sport.

The number of head impacts in soccer has also varied based on playing scenario. It has been reported that athletes receive a greater number of impacts in a game (2.7-6.9 impacts per athlete-exposure in games) than during practice (1.86-3.5 impacts per athlete-exposure in practices). We observed 6.03 impacts per athlete-exposure in games and 2.28 impacts per athlete-exposure in practices. Across all games and practices, we observed 3.3 impacts per athlete-exposure. This is lower than reported previously in women’s collegiate soccer (4.59 impacts per athlete-exposure). However, our results represent data for one collegiate women’s soccer team and may vary based on practice style. For example, some teams may participate in soccer heading drills during practice while other teams may not leading to some athletes being exposed to more head impacts during practice than other teams.

Soccer is a contact sport that results in a variety of impacts including those to the head and body. During this study non-header impacts, such as unintentional deflections, upper extremity-to-head, head-to-head, and head-to-ground impacts, resulted in greater head accelerations than body contacts, which do not involve direct head contact, and purposeful headers, which includes contact with the ball only. Hanlon et al. observed similar results with non-header impacts (22.3g) resulting in higher mean linear accelerations than header impacts (20.4g). Additionally, this study reported a mean linear acceleration of 14.4g for player falls, which is similar to our mean linear acceleration for body contacts (13.1g). Furthermore, in-lab studies
recreating non-header impacts, such as elbow-to-head (21.3g) and head-to-head impacts (35.1g, 86.5g) resulted in higher accelerations than previously reported in-lab ball-to-head impacts (16.1±1.0g, 20.3±2.8g). We observed higher accelerations from upper extremity-to-head (38.9g) and head-to-head (51.3g) impacts than ball contacts (27.4g), as well. The higher head accelerations associated with these non-header impacts may be due to these impacts being unexpected, leaving the athlete not braced for impact. Without bracing, an athlete cannot dissipate the force using their neck muscles, which could lead to greater linear accelerations.

Differences in linear acceleration by player position have been reported in sports such as football and ice hockey. There is mixed evidence in football as to which position sustains higher head accelerations, however, position has been shown to be a predictor of the number of impacts an athlete will receive, with defensive and offensive lineman sustaining more impacts than quarterbacks and wide receivers. Although data have not been previously reported in soccer, studies have shown defenders and goalkeepers as having the highest risk of head injury, which may be due to the number and magnitude of impacts they receive. In this study defenders (973) and goalkeepers (887) had the highest number of total impacts, however, midfielders had the highest magnitude impacts compared to other positions. The midfield position may have had this increase in linear acceleration due to purposeful headers from goal kicks and goalkeeper punts, which most likely resulted in the higher magnitude impacts. At this time, it is still unclear how the specific situation of contact influences the magnitude of the head impact.

Although the current study provides novel data to the area of head accelerations in women’s soccer, it is not without its limitations. Due the small sample
size (one team and one season), the generalizability across seasons and teams is not possible. Furthermore, these results are not applicable to male soccer athletes, who may be exposed to very different head accelerations. Additionally, the sensor technology used during this study is different from technology that has been previously used\cite{6,16,31,36} and therefore, comparison between technologies should be done with caution. Therefore, future studies should continue to focus on developing reliable technologies, which can be used to measure head acceleration with confidence.

In conclusion, the results of this study indicate that the head accelerations on the field in soccer appear to be influenced by factors such as playing scenario and impact type. Specifically, the non-header impacts, especially those that are unexpected can cause high head accelerations and may be of interest to clinicians or coaches because they may be more likely to cause injury. Finally, the results of this study show the importance of head acceleration research in women’s soccer as a means to further understand the immediate as well as long-term effects of heading in soccer.
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Appendix A

LITERATURE REVIEW

Contact during sports is one of the leading causes of injury in athletes today.\(^1\) With 58% of injuries occurring in games due to player-to-player contact,\(^1\) contact sports, such as football and soccer, are of the greatest concern for injury. In soccer, head and neck injuries, are among the most frequent injuries\(^1-3\) only behind, lower extremity injuries.\(^2,3\) Concussions and neck strains, for example, account for 8-15% of all injuries occurring during soccer.\(^1-7\) However, head and neck injuries may also pose risk in the long-term. There are over 300,000 sport-related concussions annually at the high school level.\(^4-6,8,16\) Sport-related concussions lead to trauma-induced alteration in mental status,\(^5\) with the potential for post-traumatic impairment.\(^6\) Still, repeated effects of impacts which do not result in concussion may cause long-term impairments, but these subconcussive impacts are still being studied.\(^10-14\) It is clear, though, that concussions and subconcussions in sports are much more common than once believed and should be regarded as a global health concern.\(^16\)

Concussions have an incidence of up to 0.40 per 1000 athlete exposures in women’s soccer,\(^1,6,9,17,18\) second only behind football.\(^4,5,9,18\) Concussions may occur as a result of both heading the ball and more commonly, non-header impacts, such as player-to-player contact.\(^2,3,5,7,17,21,22-26\) Non-header impacts may also include contact with objects other than the ball (i.e. ground, goal post, etc.).\(^2,3,5,7,17,21-26\) Specifically, player-to-player contact, such as upper extremity-to-head and head-to-head contact, during heading duels are the most frequent non-header event causing concussion.
Between 33% and 41% of concussions are due to upper extremity contact\textsuperscript{21,24} and between 28% and 32% of concussions are due to head-to-head contact.\textsuperscript{17,21,24} The variety of impacts causing concussions in soccer suggest that no one mechanism can be eliminated from the game to make soccer more safe.\textsuperscript{17,21,22}

However, when heading the ball and during player-to-player contact, neck strength may improve bracing and therefore, decrease the potential for concussion,\textsuperscript{16} as well as the resultant head acceleration.\textsuperscript{16,19,20,27} Women’s soccer athletes who have lower neck strength have been shown to be more susceptible to concussions.\textsuperscript{16} These athletes have also been shown to experience higher head accelerations than their male counterparts.\textsuperscript{27} However, neck muscle strengthening did not subsequently decrease head acceleration, making it unclear what role neck strength has in head acceleration.\textsuperscript{16,20} Additionally, unexpected impacts that occur during play may not provide athletes with time to stabilize neck musculature and may therefore be more dangerous. Therefore, more research is needed on the effects of timing and amplitude of muscle contractions.

Poor neck strength may put certain individuals more at risk of concussion than others, but player position may also increase risk. Player positions can greatly impact the number of head impacts an athlete receives. Over a 12-month period, the range in number of headers has been described between 32 and 5400, with defenders sustaining the greatest number of headers.\textsuperscript{13} This is consistent with the higher number of concussion, 67%, occurring while athletes are playing defense.\textsuperscript{17} This increased number repetitive head impacts and increased risk of concussion may put these athletes more at risk for cumulative long-term effects.
Understanding these long-term effects, as well as the many factors associated with head impacts and concussions during sport, is imperative for not only women’s soccer athletes, but all athletes, at all levels of play. It is clear that head impacts during sport expose athletes to head accelerations and therefore, quantifying head acceleration during sport is important. Although limited research is available in soccer, football has been at the forefront of head acceleration research.

**Head Accelerations and Football**

With sport-related concussions reaching epidemic levels, previous research has focused on developing a better understanding of the biomechanics associated with concussion and subconcussion in football. Concussions are common in both collegiate (0.64 per 1000 athlete exposures) and high school (0.47 per 1000 athlete exposures) football, and so research has focused on both of these groups.

One of the first studies in head acceleration research used in-helmet accelerometers (Head Impact Telemetry System, HITS) in collegiate football players during practices and games. Across 35 practices and 10 games, 3,312 impacts were observed in 38 football players. These 3,312 impacts showed an average linear acceleration of $32 \pm 25g$. There was one concussion observed, which occurred with a linear acceleration of $81g$. This acceleration value became the theoretical threshold at which it was thought concussions occurred.

Future studies have contributed to an adjusted theoretical concussion threshold. For example, Guskiewicz et al. examined head accelerations causing clinically-diagnosed concussions. Researchers observed peak linear acceleration, impact location, and clinical outcomes of concussion. In this study, 13 Division I collegiate football athletes sustained a concussion with a range in linear acceleration from 60.51
to 168.71g. There was a significant relationship between both the magnitude of impact and the location of impact and the change in clinical outcome measures. Lower magnitude impacts resulted in a slightly greater change in clinical concussion test scores 48 hours after a concussion diagnosis. Additionally, top of the helmet impacts resulted in a greater postural stability deficits when compared to other impact locations. These top of the helmet impacts also proved to be the most frequent and to cause the greatest head accelerations, with athletes receiving a blow to the top of the head being 6.5 times more likely to have a concussion. With location and concussive blows clearly having an effect on clinical symptom scores, there could be a link between the three (location of impact, acceleration, and concussion diagnosis). The concussive impacts observed in this study had a wide range in linear accelerations between 60.51g and 168.71g. However, due to this wide range in linear acceleration, establishing a true injury threshold is difficult. Additionally, with contributing factors such as impact location and previous impact history, it is unknown what factors are best predictors of concussion.

In an attempt to clarify some of these predictors, Mihalik et al. examined player position and the magnitude of impacts an athlete receives. Impacts consistently occurred between 21 and 23gs, which was significantly lower than what had been previously reported and only 0.35% of the observed accelerations were above the theoretical injury threshold of 79g. When examining player position, offensive backs were most likely to receive impacts higher than 80gs. On the other hand, offensive lineman had the highest average linear acceleration (22.89 ± 1.76g). With position taken into account a new concern was raised for our athletes, specifically those that play a particular position due to the increased head accelerations they may receive.
Additionally, due to the lower magnitude hits observed in this study, preliminary injury thresholds may have been set too high. However, no concussions were observed during this study making it difficult to determine if thresholds are accurate.

Although most research has not been successful in establishing injury thresholds, the NFL attempted to set injury thresholds on which suspicions of concussion should be raised. In 2009, these thresholds were used in collegiate football players to determine concussions as well as establish their accuracy. With the threshold of 79g set by the NFL, there were only 11 impacts that exceeded this value, with majority of impacts occurring under 20gs. Angular acceleration threshold was set at 5757 rad/sec^2, of which there were only 14 impacts that exceeded this value. Additionally, based on clinical concussion tests, none of the impacts recorded above these thresholds resulted in a concussion, further adding to the uncertainty of threshold levels. Therefore, understanding the biomechanics of these impacts as well as the human tolerance for head accelerations, may allow for more accurate thresholds to be set.

With injury thresholds under scrutiny and the need to develop a better and deeper understanding of the magnitude, type, and number of head accelerations in football athletes, studies began to change focus. In order to understand the impacts of football, the focus of research became head accelerations, number of impacts, and, more importantly, the differences that exist between impact location as well as player position.

Crisco, et al. completed multiple studies in the collegiate setting which categorized head accelerations by player position and location of impact. These studies established that location of impact and frequency of impact differed based on
player position as well as playing environment. Games resulted in a slightly higher average linear (20.2g) and angular acceleration (1197 rad/sec^2) than practices (20.0g; 1187 rad/sec^2).\textsuperscript{24} Number of impacts also differed by player position during games and practices with defensive (718) and offensive (543) lineman having the highest number of impacts during games and practices, as well as the highest number of hits to the front of the helmet (49.2%).\textsuperscript{35,38} On the other hand, running backs\textsuperscript{34} and quarterbacks had the highest magnitude hit (70.86g; 5428 rad/sec^2) and the highest frequency of hits to the back of the head (44%).\textsuperscript{35,38} These higher magnitude hits as well as more frequent hits based on player position becomes a bigger part of research later on. However, these factors such as player position and location of impact help to explain the wide range in head accelerations that can occur, but do not make setting injury thresholds based on acceleration a possibility, yet.

In an attempt to understand the biomechanics of head impacts in football in a younger population, researchers have begun to examine head accelerations in youth football. Like many sports, football athletes begin playing a very young age in the Pop Warner leagues. At this young age the brain is not fully developed and as such may be more susceptible to injury,\textsuperscript{9} which puts youth and high school athletes at greater risk of head accelerations and concussive injury than their collegiate and professional counterparts. Therefore, the cumulative effect of numerous impacts as well as the head accelerations occurring at such a young age is of concern for these athletes.

At the high school level, the average football athlete received 652 impacts over the course of a season, with lineman receiving the most (868), and receivers, cornerbacks, and safeties the least (372).\textsuperscript{29} Of these impacts the greater magnitude hits
were experienced during games. Additionally, offensive and defensive linemen received the greatest linear and angular acceleration values. The most common locations of impacts are to the back and front of the helmet. These locations also cause the greatest head acceleration. Establishing the frequency as well as some of the factors, such as player position and impact location, that affect head impacts and head accelerations, athletes who may be more at risk can be recognized. Additionally, the volume of impacts as well as higher accelerations observed by specific positions brings into question player health and safety.

At the youth level the average impact acceleration ranges from $23.26 \pm 14.40g$ to $46.70 \pm 14.00 \text{ g}$, with the highest magnitude hits occurring during practices. Impacts to the front, back, and top of the head were more likely to result in concussion. Additionally, hits that cause linear acceleration greater than $96.10g$ or rotational acceleration greater than $5582.3 \text{ rad/sec}^2$, were most likely to cause a concussion. Based on these threshold accelerations, 20% of athletes with an impact exceeding these threshold will have a concussion. This study indicates that youth athletes are exposed to high head accelerations similar to their collegiate and professional counterparts.

However, the game of football is malleable due to the various ways it can be played based on the plays run and schemes used. Martini et al. observed differences in head acceleration due to different offensive schemes. Two teams were studied based on the offensive scheme they ran, run first or pass first. The run first offense resulted in a higher number of impacts (456 vs 304), but lower linear head accelerations (25.67g) than the past first offense, which had an average linear acceleration of 28.56g and angular acceleration of $1777.58 \text{ rad/sec}^2$. Although these offensive schemes do
not offer a concrete answer to reduce head impacts, they offer insight into how the plays being run can impact head impacts as well as a possible way to reduce head impacts during practice.

Across all levels of play in football, head impacts and accelerations occur. Although there is a push to establish injury thresholds, research isn’t there yet. However, research has provided valuable insight into just how often these athletes are receiving head impacts, leading to concerns over the cumulative effects of these hits.

**Subconcussive Impacts**

Concussions are not the only concern for athletes involved in sports where the head is used during play. The cumulative effects of the repeated blows, as seen in football and soccer, could lead to neurodegenerative changes.\(^\text{10-15,29,33,38}\) With 1,408 impacts occurring across 21 collegiate women’s soccer athletes over the course of 25 matches,\(^\text{40}\) understanding the potential effects of these impacts is essential to our athlete’s health. Theses potential changes due to impacts which do not cause an athlete to present with clinically observable signs of concussion,\(^\text{10,11,13-15,29}\) are deemed “subconcussive” impacts.\(^\text{10,11,13,14}\) Although there may not be a diagnosed concussion, there is still the chance for long term neurodegenerative changes.\(^\text{10-15,29}\) An understanding of the cumulative effects of head impacts could be valuable in the attempt to make sports safer for our athletes.

Research in the area of subconcussive impacts and the potential neurodegenerative changes is still in its infancy. However, what is understood is that these subconcussive head impacts can cause axonal injury in the brain, blood brain barrier permeability changes, and neuroinflammation in the absence of noticeable behavioral changes.\(^\text{10}\) Therefore, understanding the impacts causing these changes,
without causing a concussion, will allow for a better understanding of human head acceleration tolerance.

To establish just how prevalent these neurophysiological changes are in football athletes, Breedlove et al. used MRI and ImPACT testing over the course of a season to determine if changes occur. Over the course of a season, the number of impacts were tracked, per player, as well as any concussions that may have occurred. Two athletes received concussions, but neurodegenerative changes were shown in the majority of the athletes, regardless of concussion diagnosis. Additionally, a significant relationship was established between the number of hits an athlete received and the ensuing neurophysiological deficits,\textsuperscript{11} indicating that repeated impacts could be connected to pathologically altered neurophysiology.

In a similar study, Talavage et al. used the same tests, MRI and neurocognitive testing (ImPACT) in high school football athletes to determine if repetitive head impacts resulted in neurodegeneration over the course of a season. However, this time athletes were divided into two groups those who had been previously diagnosed with a concussion and those that had not. As athletes were tested throughout the season, some began to show neurophysiological changes without having ever been diagnosed with a concussion. This led researchers to add a third category for subjects who had no clinical symptoms, but clear neurophysiological impairments. End of the season ImPACT scores showed a statistically significant decline in the impacts scores of all athletes, even if they were no diagnosed concussion.\textsuperscript{15} These differences and changes over the course of a season clearly indicate that repetitive impacts cause neurodegenerative changes.
However, football is not the only sport where athletes are subject to the effects of repetitive head impacts. Soccer heading has also been associated with such changes. Lipton et al. studied the microstructure of amateur soccer players who reported their heading activity over the past 12 months as well as concussion history. These athletes reported heading the ball between 32 and 5,400 times over the course of the previous year. This history of heading the ball was associated with changes in the brain’s white matter microstructure as well as poorer neurocognitive function. However, this change in microstructure was not related to a history of concussions and therefore, related to the athlete’s history of heading the ball during soccer play. However, it is unknown what acceleration forces are associated with these repetitive headers that do not result in concussion.

**Head Accelerations and Soccer**

Football has been the main focus of most previous head acceleration research due to the high incidence of impacts causing concussive and subconcussive blows, as well as limitations in measuring head acceleration in non-helmeted sports. However, women’s soccer is another sport that has a high incidence of concussion, which may be linked to the intentional use of the head during play as well as impacts due to player-to-player contact. This intentional use of the head exposes athletes to thousands of subconcussive impacts over the course of a career. However, head acceleration research in soccer is limited to laboratory studies. One of the first lab studies examined head accelerations during soccer heading and used pre-determined ball velocities, which mimicked heading a goal kick (16m/s) and redirecting a pass (12m/s). The straight on impact of heading a goal kick resulted in a greater average linear acceleration (32.64g) than redirecting a pass.
Researchers also tested neurocognitive function as it related to heading by pre and post testing subjects with a neurocognitive test. Unlike previous football studies, there was no degenerative changes seen over the course of 12 of headers in the lab, however, long-term changes are still possible.

To expand on these observed accelerations values, Naunheim et al. observed head acceleration with ball velocities of 9 and 12m*s$^{-1}$, linear and angular head accelerations also varied. Ball velocity of 9m*s$^{-1}$ resulted in average linear acceleration of $158 \pm 19$ m*s$^{-2}$ and average angular acceleration of $1302 \pm 324$rad*sec$^2$. On the other hand, with an increase in ball velocity (12m*s$^{-1}$) average linear ($199 \pm 27$ m*s$^{-2}$) and angular ($1457 \pm 297$rad*s$^{-2}$) acceleration also increased. However, these acceleration values are well below any threshold levels believed to cause mTBI, but the cumulative effects of these impacts is unknown.

Due to soccer being an unpredictable environment, accurately re-creating on-field heading events is difficult in the lab. However, through the use of game footage, Withnall et al. observed games for head impacts. The most commonly observed causes of head impacts in the game included elbow-to-head, lateral hand strike-to-head, and head-to-head impacts. These situations were then re-created in the lab to determine the forces that the head underwent in each situation. Elbow-to-head impacts resulted in head impact velocity of 1.7-4.7m/s which caused an average linear head acceleration of 21.3g and average angular acceleration of 1611rad/s$^2$. Lateral hand strike had the highest impact velocity of 5.2-9.3m/s causing an average linear (20.4g) and angular (1445rad/sec$^2$) head acceleration less than elbow to head impacts. Head-to-head impacts had the lowest impact velocity (1.5-3m/s), but the highest incidences of concussion as observed during the game footage, with 67% of concussions being
caused by head-to-head impacts. Additionally head-to-head impacts re-created in the lab also resulted in the greatest head acceleration. Lab re-creations were performed at 1.5m/s and 3m/s, which resulted in average linear acceleration of 35.1g and 86.7g, respectively. In regards to angular acceleration, an impact velocity of 1.5m/s resulted in an average angular acceleration of 2770rad/sec\(^2\) and an impact velocity of 3.0m/s resulted in an angular acceleration of 7033rad/sec\(^2\).\(^{26}\) These results indicate that there is a wide range in acceleration values based on the type of head impact occurring on the field. In addition, the events re-created based on game footage more closely mimicked those that are actually seen during the game of soccer thereby indicating that the acceleration values observed may more closely relate to those occurring during real time soccer play.

In the only study to date that investigated head acceleration in soccer during on-field play, Hanlon et al. reported head acceleration during six youth women’s soccer scrimmages. In this study, a total of 67 head impacts were observed (47 headers; 20 non-headers). Headers were considered impact with the ball, whereas non-headers were impacts with another object (i.e. player, goal post, playing surface). Player-to-player contacts were the most frequent non-header event, which is consistent with previous injury research.\(^{3,21,26}\) Overall acceleration values for both header and non-header events ranged in linear (4.5 to 62.9g) and angular (444.8 to 8869.1 rad/sec\(^2\)) acceleration.\(^{25}\) These acceleration values were greater than those previously reported in laboratory studies, indicating that soccer athletes may be experiencing higher than expected head accelerations during on-field play.

Soccer is a unique sport in that the head is intentionally used during play.\(^{7,17,40}\) This intentional use of the head may be putting soccer athlete’s at risk for concussion
due to the impacts received when heading the ball. However, soccer athletes may also be at risk due to the frequency and magnitude of these repetitive header and non-header events that occur everyday on the field. Cumulatively, the number of impacts these athletes receive over the course of a career is concerning and the potential for neurodegenerative changes have been shown to occur. Therefore, we need to establish a better understanding of the magnitude and frequency of these repetitive impacts, as well as the risks associated with these impacts.

**Conclusions**

Head impacts and their associated head accelerations are a part of sport play and cannot be prevented. However, there is limited information regarding the long-term effects of these impacts as well as the risks associated with their potentially high head accelerations. We do know that head impacts can cause injuries such as concussions, which are becoming more and more prevalent in all sports, not just football. Additionally, sports such as soccer and football, which subject their athletes to many repetitive impacts over the course of a career, could cause more injury than just a concussion due to the potential long-term neuropsychological damage.

Football has been extensively studied regarding the frequency as well as magnitude of head impacts that are occurring on the field, which has provided valuable information explaining the head accelerations occurring during play. However, with head impacts occurring across all sports there is a need to expand research on to the field in other sports such as soccer.

Almost exclusively, in-lab studies have quantified head acceleration during soccer, but these studies may not represent head accelerations seen during on-field
Moreover, many concussions occur from head-to-head contacts or contacts other than with the ball during purposeful heading, which most in lab studies have not observed. In the only study to-date that has quantified head acceleration during on-field play, Hanlon et al. suggested that head accelerations were higher than previously reported in a lab setting. Additionally, on-field head impact events were more likely to occur due to impacts with objects other than the ball, which most in lab studies failed to investigate. The unpredictable environment of soccer makes it difficult to re-create head impacts in the lab and, therefore, research focused on soccer, and more specifically women’s soccer is warranted.

**Limitations and Future Research**

Current head acceleration research is limited to football due to the ease of equipping helmets with head accelerometers. Additionally, the high incidence of concussion and head impacts have made observing head accelerations on a daily basis very easy. However, recently technology has developed head accelerometers to be used in non-helmeted sports. This will allow for expansion of head acceleration research into sports such as women’s soccer.

Future research should investigate the head acceleration occurring on-field during soccer play. Due to the high risk of concussion in soccer, as well as the frequently occurring head impacts, soccer athletes are at risk for both concussive and subconcussive injury. On-field monitoring of the frequency of head impacts as well as head accelerations will allow at risk athletes, due to both concussion history and frequency of head impacts, to be more closely monitored. Therefore, future studies should focus not only on head accelerations, but also the frequency of head impacts due to the possible long-term degeneration that has been shown to occur.
References


Appendix B

IRB DOCUMENT

DATE: September 25, 2015

TO: Jaclyn Caccese
FROM: University of Delaware IRB

STUDY TITLE: [500033-3] Investigation of Linear and Rotational Acceleration in Collegiate Male and Female Soccer Players During Practice and Game Play

SUBMISSION TYPE: Continuing Review/Progress Report

ACTION: APPROVED
APPROVAL DATE: September 25, 2015
EXPIRATION DATE: October 3, 2016
REVIEW TYPE: Expedited Review
REVIEW CATEGORY: Expedited review category 4

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 Maria Palazuelos at (302) 831-8619 or mariapj@udel.edu. Please include your study title and reference number in all correspondence with this office.