

# **On-Field Measurements of Head Impacts in Youth Football: Characterizing High Magnitude Impacts and Assessing Balance Outcomes**

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## **Academic Abstract**

The research presented in this thesis focuses on head impact exposure in youth football. The on-field portion of this research investigated high magnitude head impacts that youth football players experience in games and practices. With previously validated data collection methods, linear and rotational head accelerations from head impacts were collected. Over the course of two seasons, 79 total player-seasons resulted in over 13,000 impacts. A small subset of these, 979 impacts exceeding 40 g, represented the focus of this research as these impacts pose the greatest risk of injury to individuals. Some tackling drills in practice were found to have higher acceleration severities than those observed in games. How practice activities are conducted also contributes towards the overall high magnitude head impact exposure for practice, not just the practice drill itself. Within games, players who are running backs and linebackers played most frequently and experienced higher magnitude impacts more often than their teammates. Data were also collected from all players off the field. Each player completed balance assessments at the beginning and end of the season to allow for comparison, even in absence of a clinically-diagnosed concussion. Current balance assessments were observed to fall short for detecting postural control differences in this youth population. Modifications to these assessments were recommended that might allow for further insights. Research presented in this thesis will inform youth football organizations as they continue to develop strategies to enhance player safety and mitigate head impact exposure.

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## **General Audience Abstract**

The research presented in this thesis focuses on head impact exposure in youth football. The on-field portion of this research investigated high magnitude head impacts, which are associated with heightened risk of concussion, that youth football players experience in games and practices. With previously validated data collection methods, the specific causation for high risk head impacts in youth football practices and games was determined for the first time. In some practice drills, players were observed to hit harder and more frequently than they would in games. As youth practices occur more often than games do, limiting the time spent in these types of practice drills is recommended. How practice activities are conducted also contributes towards the overall high magnitude head impact exposure for practice, not just the practice drill itself. Events where players had the opportunity to get up to speed prior to impact were more likely to be high risk than events where players essentially impacted from a standstill. Data were also collected from all players off the field. Each player completed balance assessments at the beginning and end of the season to allow for comparison, even in absence of a clinically-diagnosed concussion. Current balance assessments were observed to fall short for detecting balance differences in this youth population. Modifications to these assessments were recommended that might allow for further insights. Research presented in this thesis will inform youth football organizations as they continue to develop strategies to enhance player safety and mitigate head impact exposure.

# TABLE OF CONTENTS

LIST OF FIGURES.....	v
LIST OF TABLES .....	vi
ATTRIBUTION.....	vii
CHAPTER 1: BIOMECHANICAL RESEARCH OF CONCUSSION IN YOUTH FOOTBALL POPULATIONS ..	1
OPENING REMARKS .....	1
HIGH MAGNITUDE HEAD IMPACTS .....	1
ASSESSING BALANCE.....	2
HEAD IMPACT TELEMETRY SYSTEM VALIDATION .....	2
REFERENCES.....	5
CHAPTER 2: DRILL-SPECIFIC HEAD IMPACT EXPOSURE IN YOUTH FOOTBALL PRACTICE .....	6
ABSTRACT.....	6
INTRODUCTION .....	7
MATERIALS AND METHODS .....	8
RESULTS .....	11
DISCUSSION .....	15
ACKNOWLEDGMENTS.....	19
REFERENCES.....	19
CHAPTER 3: HIGH MAGNITUDE HEAD IMPACT EXPOSURE IN YOUTH FOOTBALL.....	22
ABSTRACT.....	22
INTRODUCTION .....	23
METHODS .....	24
RESULTS .....	27
DISCUSSION .....	35
ACKNOWLEDGEMENTS .....	40
REFERENCES.....	40
CHAPTER 4: POSTURAL CONTROL IN YOUTH FOOTBALL PLAYERS: A COMPARISON OF THE BALANCE ERROR SCORING SYSTEM AND A FORCE PLATE PROTOCOL .....	44
ABSTRACT.....	44
INTRODUCTION .....	44
METHODS .....	46
RESULTS .....	50
DISCUSSION .....	55
ACKNOWLEDGMENTS.....	60
REFERENCES.....	60
CHAPTER 5: CLOSING REMARKS .....	67
RESEARCH SUMMARY .....	67
PUBLICATION OUTLINE .....	68

## LIST OF FIGURES

FIGURE 2.1: IMPACT RATE BY DRILL. ....	13
FIGURE 2.2: LINEAR AND ROTATIONAL HEAD ACCELERATION DISTRIBUTIONS BY DRILL. ....	14
FIGURE 2.3: QUANTIFIED PRACTICE STRUCTURE. ....	18
FIGURE 3.1: HIGH MAGNITUDE IMPACTS BY CAUSE AND PART OF FIELD. ....	30
FIGURE 3.2: COMPARISON OF GAME PLAYS TO HIGH MAGNITUDE IMPACTS. ....	32
FIGURE 3.3: IMPACT RATES FOR ALL FOOTBALL ACTIVITIES BY TEAM. ....	35
FIGURE 4.1: NUMBER OF ERRORS BY BESS STANCE. ....	51
FIGURE 4.2: OVERALL BESS SCORE BY TEST DATE. ....	51
FIGURE 4.3: COMPARISON OF EYES OPEN AND EYES CLOSED FORCE PLATE TRIALS. ....	53
FIGURE 4.4: CORRELATION BETWEEN PATH METRICS. ....	54
FIGURE 4.5: CORRELATION OF BESS STANCES WITH RECOMMENDED BESS PROTOCOL. ....	56
FIGURE 4.6: COMPARISON OF BESS PROTOCOL AND THE BESS PROTOCOL RECOMMENDED BY THIS STUDY. ....	57

## LIST OF TABLES

TABLE 1.1: SUMMARY OF HIT SYSTEM VALIDATION TEST LOCATIONS AND SPEEDS.....	4
TABLE 2.1: PRACTICE DRILLS ASSOCIATED WITH > 40G IMPACTS.....	10
TABLE 2.2: PRACTICE DRILL FREQUENCY AND SEVERITY.....	12
TABLE 3.1: PLAYER POSITION GROUPINGS.....	26
TABLE 3.2: SUMMARY OF HIGH MAGNITUDE HEAD IMPACT EXPOSURE BY TEAM.....	28
TABLE 3.3: SUMMARY OF GAME IMPACTS BY POSITION.....	31
TABLE 3.4: SUMMARY OF HIGH MAGNITUDE IMPACTS BY POSITION.....	33
TABLE 3.5: PRACTICE STRUCTURE BY TEAM.....	38
TABLE 4.1: SUMMARY OF PATH CHARACTERISTICS AND METHOD OF CALCULATION.....	48
TABLE 4.2: R <sup>2</sup> VALUES BY BESS STANCE.....	50
TABLE 4.3: COP METRICS FOR FORCE PLATE ANALYSIS.....	52
TABLE 5.1: PUBLICATION PLAN FOR RESEARCH FROM THIS THESIS.....	68

## **ATTRIBUTION**

The research presented in this thesis not only represents my own efforts, but also the efforts of several colleagues. Their contributions are summarized below.

Ryan A. Gellner, BS (Center for Injury Biomechanics, School of Biomedical Engineering and Sciences) is currently a Graduate Research Assistant at Virginia Tech. Ryan was a co-author and assisted with data collection and analysis. *Contributed towards Chapter 3.*

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# **Chapter 1: Biomechanical Research of Concussion in Youth Football Populations**

## **OPENING REMARKS**

Football is associated with a high incidence rate of concussion when compared to other team sports. Most of the biomechanical research that has investigated football impacts has focused on high school, collegiate, or professional populations. Youth populations (< 14 years old), though, represent nearly 70% of all football players in the United States. The limited amount of research conducted at the youth level to this point has been largely superficial. The objective of this work was to determine the specific football activities youth players are exposed to that would be most likely to result in concussion. This work also explored the effectiveness of using balance tests as a clinical tool within this population. All work is aimed at promoting player safety in youth football.

## **HIGH MAGNITUDE HEAD IMPACTS**

Linear acceleration has been shown to be related to risk of concussion, in that exposure to higher magnitude linear accelerations increases the risk of concussion. The on-field research within this thesis focused primarily on these high magnitude impacts (linear accelerations exceeding 40 g). These impacts are verifiable through video analysis and the specific environment surrounding the impact can be characterized. By gaining a deeper understanding of what activities lead to these high magnitude head impacts, pointed efforts to limit contact or change rules to reduce the incidence of such impacts can be carried out. The methodologies and recommendations set forth may be used by coaches and leagues around the country.

## **ASSESSING BALANCE**

Decreased postural control and struggles to maintain balance are known symptoms after sustaining a concussion. Several balance tests have been developed by clinicians and sports personnel to assess these balance issues in concussed athletes and clear athletes to return to play. The Balance Error Scoring System (BESS) is a series of 6 trials that ask participants to hold their balance in positions of varying difficulty. The BESS is scored by an observer who keeps track of errors made by the subject. A less subjective assessment involves subjects standing on a force plate and maintaining balance. This quantification of balance may be more useful in accurately assessing postural control. Similar to head impact exposure research, most balance research has focused on adult populations. As children are still developing balance, it is essential to assess the effectiveness of these commonly used clinical tools for youth populations.

## **HEAD IMPACT TELEMETRY SYSTEM VALIDATION**

The Head Impact Telemetry (HIT) System has been tested previously in a variety of conditions. These studies have utilized similar test methods, with different speeds and locations to assess the effectiveness of the HIT System to measure peak acceleration values when compared to an instrumented headform.

Beckwith et al. utilized a linear impactor, but explored only 4 impact locations.<sup>1</sup> These locations were selected based on NFL reconstruction of concussive impacts and can best be defined as Facemask, Side, Front Boss, and Rear Boss.<sup>5</sup> Impact speeds were also extracted from the NFL reconstruction data. The three highest speeds represented the average speed,  $\pm 1$  standard deviation, from all concussive impacts. The low speed tested represents a standard deviation below the average, non-concussive speed observed in that study. Each location and speed were tested a minimum of 3 times. High levels ( $R^2 > 0.8$ ) of correlation were observed between the HIT System and the reference measurements from a HIII dummy. For impacts to the facemask,

$R^2$  values were below 0.6. The HIT System was observed to overpredict linear acceleration by less than 1%, while underestimating rotational acceleration by 6.1%. In individual impacts, error in acceleration magnitude varied from 0.1-38.9%.

Manoogian et al. conducted helmet-to-helmet tests to compare measurements of head acceleration and helmet acceleration.<sup>4</sup> Head acceleration was found to be less than 10% of helmet acceleration. For accelerations ranging from 5 to 50 g, the HIT System and reference system measured similar acceleration magnitudes.

Jadischke et al. conducted 2 series of impact tests to assess the HIT System. Firstly, a linear impactor was used to test at 4 locations.<sup>3</sup> A single impact speed was used, the average value reported for concussive impacts in the NFL reconstruction research.<sup>5</sup> Each impact was repeated between 3 and 6 times. The second test series impacted several locations on the facemask, in addition to other helmet locations. When compared to reference data from the Hybrid III, individual measurement error in peak linear acceleration was between 10-20%. For helmet shell impacts, average relative error below 6% was observed, as was the case with the Beckwith study. Impacts to the facemask were associated with the greatest error in HIT System measurement and what was measured by the Hybrid III. For the Front Boss and Side locations, HIT System acceleration values more closely matched the Hybrid III measurements. Impacts to the Rear Boss location, though more accurately measured than facemask impacts, were less accurate than either the Front Boss or Side acceleration measurements.

Siegmund et al. tested the HIT System using a linear impactor at 12 locations on the helmet, 3 of which made contact with the facemask initially.<sup>6</sup> Impact speeds were determined based on speeds used in the reconstruction of NFL impacts.<sup>5</sup> Tests were conducted at each location and speed 16 times. For most test locations, acceleration values calculated by HITS differed from the

reference acceleration by more than 25%. These included the Facemask, Crown, Low and High Rear, as well as Rear Eccentric locations. Locations that did not differ more than 25% from the reference values included the Side, Jawpad, Front Eccentric, Front Boss, and Forehead. Acceleration values for impacts to the rear of the helmet appear to be less accurately calculated than for those towards the front or side of the helmet. Impacts to the facemask do not result in accurate measurements either.

**Table 1.1: Summary of HIT System validation test locations and speeds**

<b>Study</b>	<b>Impact Location</b>	<b>Test Speed (m/s)</b>
<b>Siegmund et al.<sup>5</sup></b>	<b>Forehead, Front Boss, Rear Boss, Side, Low Rear, Facemask, Oblique, Front Eccentric, and Rear Eccentric</b>	<b>3.6, 5.5, 7.4, 9.3, and 11.2</b>
	<b>Crown, Jaw Pad</b>	<b>3.6, 5.5, 7.4, and 9.3</b>
	<b>High Rear</b>	<b>3.6, 5.5, and 7.4</b>
<b>Beckwith et al.<sup>1</sup></b>	<b>Facemask, Side, Front Boss, and Rear Boss</b>	<b>4.4, 7.4, 9.3, and 11.2</b>
<b>Manoogian et al.<sup>3</sup></b>	<b>Side, Back, Top, and Forehead</b>	<b>2.0, 3.5, and 5.0</b>
<b>Jadischke et al.<sup>4</sup></b>	<b>Forehead, Front Boss, Side, and Rear Boss</b>	<b>9.3</b>
	<b>Low, Middle, and High Facemask, High Front Boss, Side, and Rear Boss</b>	<b>5.0, 7.4, 9.3, and 11.2</b>

Using previously published datasets, Cobb quantified the effect of error within individual measurements from the HIT System.<sup>2</sup> For the HIT System, random measurement error was  $\pm 15.7\%$  for peak resultant linear acceleration and  $31.7\%$  for peak resultant rotational acceleration. Using Monte Carlo techniques, the effect of these individual measurement errors when extracting estimates from the overall dataset was computed. The greatest uncertainty was observed at 95<sup>th</sup> percentiles values, where uncertainty values were 0.5 g for linear acceleration and 33 rad/s<sup>2</sup> for rotational acceleration. Further, increasingly larger datasets were shown to reduce the uncertainty in estimating statistical estimates from the dataset to below 5% error in most cases. Though individual measurement error may vary considerably from a “true” acceleration value, the effects

of these random errors are mitigated when exploring hundreds or thousands of head impacts to determine representative statistical estimates.

Many of the highest errors reported in previous validation studies have been the result of impacts to the facemask. These impacts alter the positioning of the helmet and can decouple the accelerometers from the head, thus limiting the ability of the HIT System to accurately measure impact accelerations. Further, impacts towards the rear of the helmet seem to be less accurately measured than impacts to other locations on the helmet shell. While the HIT System has been shown to be limited in accurately measuring acceleration values for single impacts, this effect is limited when looking at a large number of impacts.

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## **Chapter 2: Drill-Specific Head Impact Exposure in Youth Football Practice**

### **ABSTRACT**

Although 70% of football players in the United States are youth players (6-14 years old), most research on head impacts in football has focused on high school, collegiate, or professional populations. The objective of this study was to identify the specific activities associated with high-magnitude (acceleration > 40g) head impacts in youth football practices. A total of 34 players (age of  $9.9 \pm 0.6$  years) on 2 youth teams were equipped with helmet-mounted accelerometer arrays that recorded head accelerations associated with impacts in practices and games. Videos of practices and games were used to verify all head impacts and identify specific drills associated with each head impact. A total of 6813 impacts were recorded, of which 408 had accelerations exceeding 40g (6.0%). For each type of practice drill, impact rates were computed that accounted for the length of time that teams spent on each drill. The tackling drill King of the Circle had the highest impact rate (95% CI 25.6-68.3 impacts/hr). Impact rates for tackling drills (those conducted without a blocker [95% CI 14.7-21.9 impacts/hr] and those with a blocker [95% CI 10.5-23.1 impacts/hr]) did not differ from game impact rates (95% CI 14.2-21.6 impacts/hr). Tackling drills were observed to have a greater proportion (between 40 and 50%) of impacts exceeding 60g than games (25%). The teams in this study participated in tackling or blocking drills for only 22% of their overall practice times, but these drills were responsible for 86% of all practice impacts exceeding 40 g. In youth football, high-magnitude impacts occur more often in practices than games, and some practice drills are associated with higher impact rates and accelerations than others. To mitigate high-magnitude head impact exposure in youth football, practices should be modified to decrease the time spent in drills with high impact rates, potentially eliminating a drill such as King of the Circle altogether.

## INTRODUCTION

It is estimated that between 1.6 and 3.8 million sports-related concussions occur in the United States each year.<sup>6,16</sup> Sports-related concussions have been the subject of much public attention due to research suggesting potential long-term effects resulting from these brain injuries.<sup>25</sup> Football has been linked to the highest incidence of brain injury among team sports, spurring a great deal of biomechanics research related to concussions and football.<sup>3-6,11,16,19,20,22,23</sup> The prevailing thought for concussion mitigation in football today is to limit exposure to head impacts through proper teaching and rule modification.<sup>10</sup>

Head impact biomechanics research for football has largely relied on outfitting athletes with helmet instrumentation during play to collect head impact data. This research has resulted in data on millions of head impacts, which have been used to quantify tolerance to concussion and characterize head impact exposure in football.<sup>15</sup> Most research on head impact exposure in football has focused on high school, collegiate, and professional populations, despite the fact that 70% of all football players in the United States are youth players (6-14 years old).<sup>13</sup> Recently, researchers have begun to use instrumentation such as helmet-mounted accelerometer arrays to collect data on youth football to quantify head impact exposure and assess concussion tolerance.<sup>7,13,14,27</sup> Daniel et al. provided 7 players (7-8 years old) with helmets equipped with instrumentation to measure head impacts. With the use of these helmets, Daniel et al. demonstrated that more high-magnitude impacts occurred in practice than in games.<sup>13</sup> The findings from that study were part of the process that ultimately led to rule changes in the Pop Warner youth sports organization that were aimed at mitigating head impact exposure in youth football.<sup>21</sup> The following year, Cobb et al. followed 3 youth football teams with players 9-12 years of age and found that teams adhering to the policy changes experienced a 40% reduction in overall impacts relative to those that did not.<sup>7</sup> Due to differences in age, head impact magnitude and frequency were found to be greater in the study by

Cobb et al. than in the study by Daniel et al., although both magnitude and frequency were still less than that found in older populations.<sup>12,26</sup>

While these studies provided valuable insight regarding head impact exposure in youth football players, they investigated practices and games as a whole, with little analysis quantifying the causation of high-magnitude impacts, which are associated with higher risks of head injury. The objective of this study was to analyze youth football practices and determine which drills were associated with the highest magnitude impacts. Secondly, this study aimed to determine how representative practice drills were of games by comparing impact rates between practices and games. This analysis represents a first step towards developing data-driven efforts to improve player safety in youth football. Conducted on a larger scale, these methods and the resulting data could be used to inform further policy changes to mitigate head impact exposure in youth football.

## **MATERIALS AND METHODS**

Two youth football teams composed of 9- to 11-year-old players were included in this study, which was approved by the Virginia Tech Institutional Review Board. Guardians provided written consent, and the youth players verbally assented to participation. A total of 34 players were recruited and chose to participate. Each received a helmet instrumented with accelerometer arrays (Head Impact Telemetry [HIT] System, Simbex). Study participants had a mean age of  $9.9 \pm 0.6$  years and a mean body mass of  $37.4 \pm 9.6$  kg. Between the 2 teams, data collection comprised a total of 65 sessions, of which 55 were practices and 10 were games.

The HIT System consists of a 6-accelerometer array that is mounted inside of Riddell Revolution or Speed helmets. A 10g resultant acceleration threshold was used to distinguish between actual impacts and acceleration levels that could be attained by simply jumping or running quickly.

The accelerometers are spring mounted so that contact with the head is maintained for the duration of impact. This ensures measurement of head acceleration, rather than helmet acceleration.<sup>17</sup> Players wore the instrumented helmets at each practice and game throughout the season. Helmet instrumentation collected data continuously, but when an individual data channel exceeded the 14.4g threshold, data acquisition was automatically triggered, capturing 40 msec of data, including 8 msec of preimpact data. Impact data were then wirelessly transmitted from the helmets to a sideline computer, in which linear and rotational accelerations were computed.<sup>8,23</sup>

Games and practices were filmed to facilitate video verification of head impacts. For every impact greater than or equal to 40g in practice, video was also used to identify the specific drill/activity associated with impact. Each of these impacts was assigned to one of 9 practice drill classifications (Table 1). Game impacts exceeding 40g were also verified to allow for comparison of high-magnitude head impact rates between practices and games.

Investigating practices at the drill level required determination of numbers of impacts and time spent for each drill type. Practice film and activity logs kept for each day of practice were used to determine the total time spent participating in each drill type. Both the number of impacts and time spent in a drill varied greatly over the course of the season, necessitating the use of a normalized impact rate for comparisons to be made. Impact rates were computed on a per-hour basis to characterize each drill type. Byar's method, which represents an exact approximation to the Poisson distribution and retains high levels of accuracy for both small and large counts, was used to compute 95% confidence intervals for the impact rates in this study.<sup>2</sup> Boxplots were developed for each drill type for both linear and rotational resultant acceleration. The first and third quartiles enclose the box, with any data points beyond 1.5 times the interquartile range from the first or third

quartile defined as outliers.<sup>18</sup> The corresponding impact rates and boxplots were also calculated for games to provide a means of comparison.

**Table 2.1: Practice drills associated with > 40g impacts. Each impact over 40g was classified as being associated with one of the following drills. Most drills, even those not designated as tackling drill, resulted in tackling.**

Drill Type	Description
Blocking Drill	Drills focused on teaching blocking
Tackling Drill – Blocker Present	At least 1 blocker present as well as a ball carrier and tackler.
Tackling Drill – No Blocker Present	Only a ball carrier and tackler participate
King of the Circle	Tackling drill: player in middle of circle rushes at player on perimeter of circle.
Scrimmage	Full 11 vs. 11 offense vs. defense
Offense vs. Defense	Small-scale (5 vs. 5 up to 8 vs. 8) offense vs. defense
Offense or Defense	11 offensive or defensive players with 3-4 proxy players on the other side
Passing or Running Drills	Pass catching or rushing drills
Other	All other practice activities

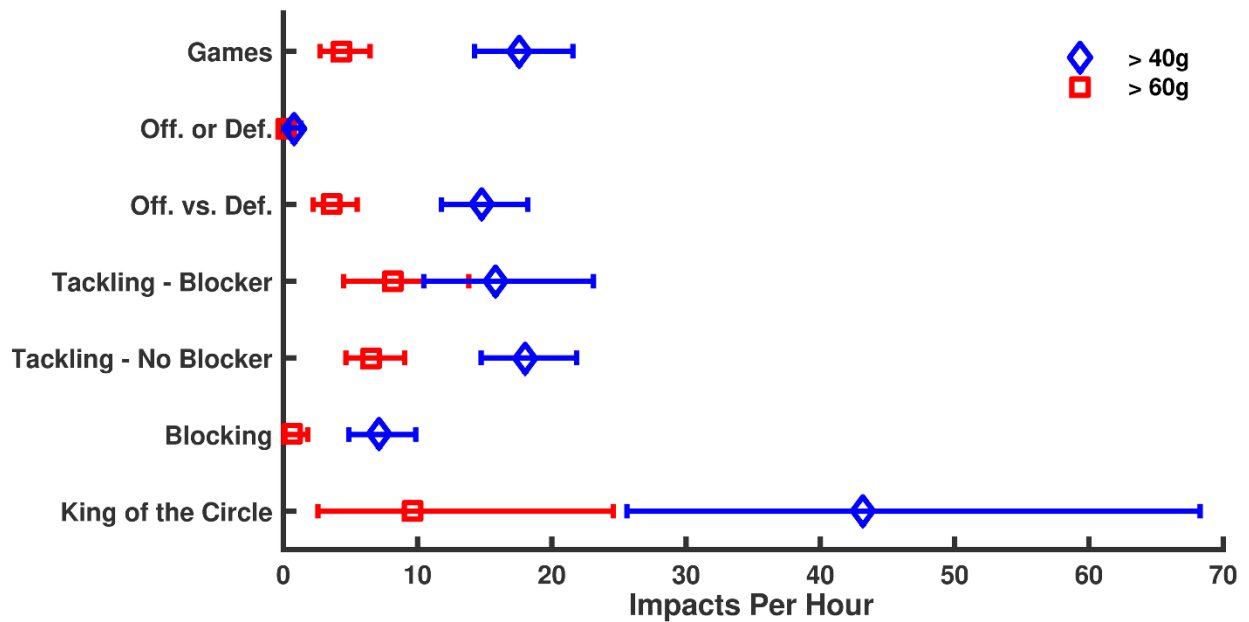
## RESULTS

For the season, a total of 6813 impacts were recorded and verified from instrumented players, of which 408 had accelerations exceeding 40g. These impacts were video-verified, with 314 (77%) occurring in practice and the remaining 94 (23%) in games. Of 6813 overall season impacts, 408 (6.0%) total impacts exceeded 40g, 118 (1.7%) exceeded 60g, and 59 (0.9%) exceeded 70g. Although assessment of player injury was deferred to usual league protocol in instances of suspected concussion, no players in the study sustained a clinically-diagnosed concussion.

The greatest number of impacts greater than 40g occurred in tackling drills, even though they were practiced only half as often as organized offensive or defensive drills (Table 2). A 40g acceleration value was selected as the threshold for high-magnitude impacts which included the top 6% of impacts that players in this study experienced, while the 60g threshold included the top 2% of impacts and is within the range of previously measured concussive impacts in this population (concussions at the youth level have been reported at 58g and 64g).<sup>7</sup> Drills involving tackling resulted in a higher rate of impact than those that did not (Fig. 1). Increasing severity thresholds resulted in lower rates of impact across all drills. Overall, impact rates for games (95% CI 14.2-21.6 impacts/hr) did not vary greatly from those for tackling practice drills (those conducted without a blocker [95% CI 14.7-21.9 impacts/hr] and those with a blocker [95% CI 10.5-23.1 impacts/hr]), with the exception of King of the Circle, which had the highest impact rate (95% CI 25.6-68.3 impacts/hr). This trend was consistent for all acceleration severity thresholds.

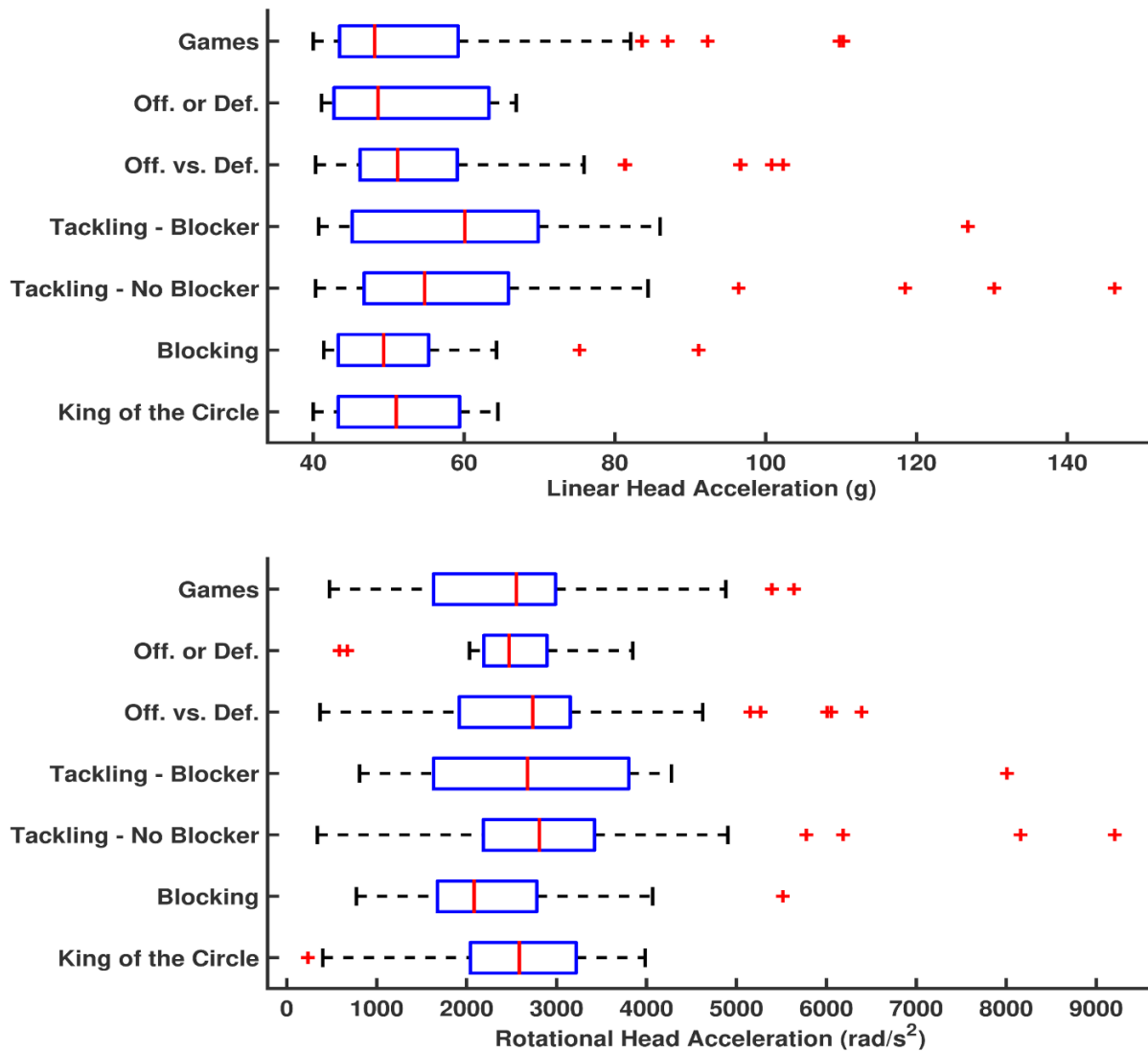
**Table 2.2: Practice drill frequency and severity. Impact frequency decreases with increasing impact severity for all drill types. Drills resulting in tackling produced more high-magnitude impacts than those that do not. Most time was devoted to drills that most closely replicate a game environment.**

	Drill Type	Time Spent in Drill (hrs/season)	Number of Impacts > 40g	Number of Impacts > 50g	Number of Impacts > 60g	Number of Impacts > 70g	Number of Impacts > 80g
<b>Tackling</b>	Tackling Drill - No Blocker	5.767	104	65	38	21	7
	Tackling Drill - Blocker	1.700	27	19	14	7	2
	King of the Circle	0.417	18	10	4	0	0
	Off. Vs. Def.	5.833	86	48	21	11	7
<b>Skill</b>	Blocking Drill	4.817	34	16	3	2	1
	Scrimmage	1.250	11	5	3	0	0
	Off. or Def.	15.800	12	6	4	0	0
	Running or Passing	3.783	14	9	2	1	1
	Other	0.850	8	6	6	3	3
	Games	5.333	94	40	23	14	6



**Figure 2.1: Impact rate by drill. King of the Circle led to the highest impact rate of all practice drills (25.6-68.3 impacts/hr). Drills resulting in a tackle were found to lead to higher impact rates. Symbols represent the mean and bars represent the 95% CIs. Def. = defense; Off. = offense.**

Distributions of both linear and rotational acceleration magnitudes varied between drill types and games (Fig. 2). Tackling drills were associated with greater severity head impacts than nontackling drills. Furthermore, the proportion of impacts greater than 60g was higher in tackling drills (between 40 and 50%) than in games (25%). Similar trends were observed for rotational acceleration, with tackling drills being associated with a greater proportion of high-magnitude accelerations than nontackling drills or games.



**Figure 2.2: Linear and rotational head acceleration distributions by drill. Tackling drills were found to have the largest proportion of impacts over 70g. Tackling drills were associated with a greater acceleration severity than games. Tackling drills comprised Tackling – Blocker, Tackling – No Blocker, King of the Circle and Offense vs. Defense. All other drills were considered Skill Drills. Only impacts exceeding 40g were included. The *red line* in each box denotes the median; *boxes*, the interquartile range; and *plus signs*, the outliers. The *whiskers* represent the threshold for defining a point as being within the data set or being an outlier. They are defined to be 1.5 times the interquartile range from the first or third quartile. If an outlier did not exist for a particular drill, then they represent the minimum and maximum in that scenario.**

## DISCUSSION

Previous work on youth football head impact exposure has investigated magnitude and frequency of impacts but has yet to explore the specific causation of high-magnitude head impacts.<sup>7,13,14,27</sup> The proportion of high-magnitude head impacts (those exceeding 40g) in youth practices (77%) was similar to the 79% found by Daniel et al.<sup>13</sup> Furthermore, the proportion of high-magnitude impacts for severity thresholds of 40g and 60g was consistent with that observed by Cobb et al.<sup>7</sup> This relationship between high-magnitude impacts in practices and games contrasts with that observed in high school and collegiate football, where high-magnitude impacts were more often observed in games than in practices.<sup>4,9,10,24</sup> Efforts aimed at reducing high-magnitude impacts in practices necessitate an evaluation of practice drill structure.

Impact rate differed markedly between practice drills with and without tackling for all severity levels. Impacts without tackling resulted in fewer than 10 impacts above 40g per practice-hour while drills involving tackling exceeded this by at least a factor of 2. King of the Circle produced high-magnitude impacts more frequently than any other activity because of the speed at which it is performed (Fig. 1). A ball carrier in the middle of a circle rushes at 3 different defenders on the perimeter of the circle. When the ball carrier rushes at each defender on the perimeter, he must be tackled. The drill continues until each player has had the opportunity to be the ball carrier. Notably, this drill was carried out for the shortest amount of time of all drills assessed. Furthermore, no impact from King of the Circle exceeded 70g (Table 2). Tackling drills, with or without blockers, were associated with the highest proportion of impacts over 70g. The presence of the blocker did not have an effect on the impact rate. This suggests that the end goal of tackling has more bearing on high-magnitude impact rate than does the drill environment itself. Furthermore, the practice drill aimed at teaching blocking (Blocking) was associated with a lower impact rate for all severity thresholds when compared with tackling drills that involve players engaging with a blocker

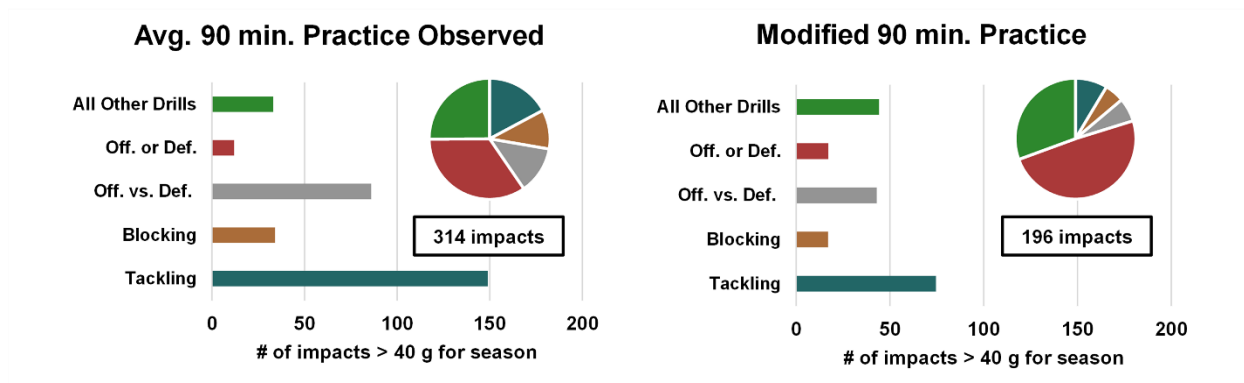
(Tackling – Blocker). In comparing the tackling drills, which only differed in whether or not a blocker was present to engage with the tackling defender (Blocker or No Blocker), we observed that a greater proportion of higher magnitude impacts was associated with the drill when a blocker was not present (Fig. 2). Reducing time spent in drills of this nature can limit the frequency at which youth players are exposed to high-severity head impacts.

Both teams in the study spent about 3-fold as much time conducting the Offense or Defense drill compared with the next most popular drill, Offense vs. Defense (Table 2). The Offense or Defense drill resulted in a very low rate of impact and closely mimicked game play because it effectively served as an opportunity for the players to practice game plans and positioning. Offense vs. Defense also exhibited fidelity to game situations, and the higher impact rate observed stems from the smaller number of players involved. With more open space in the field of play, players were able to achieve greater running speeds and thus produce higher-magnitude head impacts. The Offense or Defense drill allowed the teams to have 11 players on one side of the ball and work more on execution of plays. The Offense vs. Defense drill opposed an offense and a defense with neither side having 11 players, with the goal being to simulate the physical side of the game. It should be noted that the small size of the teams (neither team exceeded 20 total players) prevented the teams from being able to conduct intrasquad scrimmages (11 players on each side of the ball) that would best represent a game situation.

Drills involving tackling were associated with impact rates similar to game rates, excluding King of the Circle (Fig. 1). However, tackling drills were associated with a greater proportion (between 40 and 50%) of impacts exceeding 60g than games (25%). Even though most practice drills did not result in impact rates higher than those in games, practices led to a greater number of high-magnitude head impacts because there were more practices than games. The greater

proportion of high-magnitude game impacts between 40g and 60g suggests that specific practice drills, primarily those that involved tackling, expose youth football players to more severe impacts than would be experienced in game play (Fig. 2).

Each practice session lasted 90 minutes, approximately 40 of which were spent in non-football drill activities, such as running, stretching, instruction, and water breaks. On the season, 88% of the remaining 50 minutes was spent in one of the drills specified in Table 1, with the remaining 12% in drills that did not result in high-magnitude impacts. On average, this corresponded to 17 minutes spent in Offense or Defense, 9 minutes in tackling drills, 6 minutes in Offense vs. Defense, 5 minutes in blocking drills, and the remaining 13 minutes in all other drills. The teams in this study participated in tackling or blocking drills for only 22% of their overall practice times, but these drills were responsible for 86% of all practice impacts exceeding 40g. If these 2 teams reduced the time spent in tackling or blocking drills by 5 minutes each practice, this would result in a 19% decrease in practice impacts over 40g. Similarly, a 10-minute reduction would result in a 38% decrease in such impacts (Fig. 3). A 50% reduction in high-magnitude impacts would be observed in tackling and blocking drills with this reduction. To further reduce high-magnitude head impacts, the King of the Circle drill could be eliminated from youth practices because the very high impact rate was not representative of games.



**Figure 2.3: Quantified practice structure. In each 90-minute practice session, teams spent an average of 50 minutes practicing drills. A 10-minute reduction split between Tackling, Blocking, and Offense vs. Defense drills would result in a 38% decrease in high-magnitude head impacts over the course of the season. The pie charts represent the proportion of the 50 minutes on average of practice time that were spent in each drill.**

Certain limitations of this study should be noted. The HIT System is associated with error up to 15.7% for individual acceleration measurements, although the mean overall error for many measurements is only 1%.<sup>1</sup> Individual acceleration measurements were used to determine impacts that exceeded the 40g study threshold. Beyond that, the resulting analysis characterized distributions of data for which the effect of this error would be minimized.<sup>7</sup> Other factors limit the applicability of these results to other situations. Just as the 2 teams here exhibited differences in head impact exposure and practice style, profiles of head impact exposure and practice structure likely will vary between teams and individuals.<sup>9-12</sup> Head impact exposure and practice structure will vary by age group,<sup>3-5,7,11-14,27</sup> and game-to-practice ratio will vary by team and league.

Head impact kinematic data for 2 youth football teams of players 9-11 years old were collected to assess the effect of specific practice drills on impact exposure and their relation to game situations. For all impacts exceeding 40g, rates of impact for the most severe drills (those with the highest-magnitude impacts) do not differ from those attained in games. At greater thresholds, up

to 80g, tackling drills resulted in greater impact rates than games. These data suggest that a substantial reduction in high-magnitude head impacts in youth football could be attained through limiting the amount of contact in practice. Even though much practice time was spent in noncontact scenarios and several high-magnitude impacts reported in this study occurred in noncontact situations, contact drills were associated with the majority of impacts over 40g. Coaches and league organizers can use these data to make informed decisions on practice structure that will help to reduce exposure to high-magnitude impacts. Further research into practice drill impact exposure at all levels of football is necessary to increase player safety and to characterize head impact exposure on a larger scale.

## **ACKNOWLEDGMENTS**

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## **Chapter 3: High Magnitude Head Impact Exposure in Youth Football**

### **ABSTRACT**

Even in absence of a clinically-diagnosed concussion, neurocognitive changes may develop as a result of playing football. The objective of this study was to determine the specific causation of high magnitude impacts (accelerations exceeding 40 g) in youth football games and to assess how representative practice activities were of games. A total of 45 players (mean age  $10.7 \pm 1.1$  years) on 2 youth teams received helmets instrumented with accelerometer arrays to record head impact accelerations for all practices and games. Video from practices and games was used to verify all high magnitude head impacts, identify specific impact characteristics, and determine the amount of time spent in each activity. A total of 7590 impacts was recorded, of which 571 resulted in accelerations exceeding 40 g (7.5%). Impacts were characterized based on the position of the impacted player, the part of the field in which the impact occurred, and the cause of impact. High magnitude impacts in the open field occurred most frequently in both games (60.0%) and practices (69.0%). Back players experience a greater proportion of high magnitude head impacts than players at other positions. The two teams in this study structured practice similarly insofar as time spent in each drill, but impact rates differed for each drill between the teams. Coaching style and practice intensity, and not just practice drills themselves, can alter head impact exposure. Though game impact rates exceeded those for practice, teams practice more frequently and are exposed to an overall greater number of high magnitude head impacts. Limiting or modifying contact/tackling drills in practice represents an opportunity to reduce the risk of concussion for youth football players.

## INTRODUCTION

With research positing that long-term neurocognitive deficits may result from repetitive sports-related concussions, these injuries have been thrust into the public sphere.<sup>21,29</sup> Of all sports, football accounts for the highest number of concussions.<sup>19,20,31</sup> Head impact exposure in football has even been shown to result in neurocognitive and brain changes in absence of a clinically-diagnosed concussion.<sup>1,18,30</sup> Most research quantifying head impact exposure in football has focused on high school, collegiate, or professional populations despite youth football players representing 70% of all players in the United States.<sup>4-6,9,14,22,24-26,28</sup> Proper teaching and rule modification are considered to be effective methods for limiting head impact exposure and mitigating concussions in football.<sup>13</sup>

Using helmet-mounted accelerometer arrays, previous research with youth football players has shown that most head impacts occur in practice.<sup>8,10,16,33</sup> The first of these studies was instrumental in developing rule changes that the Pop Warner youth organization instituted to limit head impact exposure for youth football players.<sup>16</sup> Following these changes, it was observed that head impact exposure can be reduced by as much as 40% by limiting contact in practice.<sup>10</sup> A classification system developed to assess the number of high magnitude impacts produced by specific practice drills found that most tackling drills were associated with a greater impact severity than game impacts.<sup>8</sup> These studies were consistent with previous research in that the youth populations studied experienced head impacts in lower magnitudes and frequency than older populations.<sup>8,10,16,17,26,32,33</sup>

Quantification of impact exposure for games, to this point, has been limited to either frequency or impacts per game.<sup>10,14,16,17,24,33</sup> While this research has been invaluable in promoting player safety, it has provided a largely superficial investigation into the circumstances surrounding game impacts, specifically those of a high magnitude. These high acceleration magnitude impacts

are associated with a greater risk of concussion than lower acceleration impacts.<sup>27</sup> With a valuable framework already in place to assess head impact exposure in football practices,<sup>8</sup> the primary objective of this study was to quantify high magnitude impact exposure in games and compare that to practice. These data have applications towards improving player safety in youth football by developing interventions that limit head impact exposure.

## **METHODS**

Two youth football teams composed of 9-12 year old players were included in this study approved by the Virginia Tech Institutional Review Board. All participants verbally assented and their guardians provided written consent. A total of 45 players chose to participate and received helmets instrumented with accelerometer arrays (Head Impact Telemetry [HIT] System, Simbex). Players on the Junior team (Juniors) had a mean age of  $9.9 \pm 0.6$  years and a mean body mass of  $38.9 \pm 9.9$  kg. Players on the Senior team (Seniors) had a mean age of  $11.9 \pm 0.6$  years and a mean body mass of  $51.4 \pm 11.8$  kg. Overall, data collection consisted of 55 practice sessions and 14 games. Juniors conducted 25 practices, compared to 30 for Seniors. Both played 7 games.

All players were provided a Riddell Revolution or Speed helmet with a six accelerometer array mounted inside. To ensure measurements of head acceleration, and not helmet acceleration, the accelerometers are spring-mounted to maintain contact with the head throughout the impact.<sup>23</sup> Players wore the instrumented helmets at each practice and game throughout the season. Data acquisition for impacts was automatically triggered when an individual channel exceeded a 14.4 g threshold. A 10g resultant acceleration threshold was used to distinguish between impact events and accelerations levels associated with non-impact events. Impact data, which were transmitted wirelessly from the helmets to a sideline computer, were processed to compute linear and rotational resultant accelerations.<sup>11,28</sup>

Games and practices were filmed to facilitate video verification of head impacts. Any impact exceeding 40 g was categorized as a high magnitude impact, which is consistent with previous work and represented the top 8% of all impacts recorded. All high magnitude head impacts were visually verified in order to identify the scenario associated with the head impact. Activity logs for each session were used to parse out spurious impacts most often associated with players dropping their helmets on the ground during breaks in action. Game video was also used to develop offensive and defensive play counts for each player.

All high magnitude impacts were classified as either occurring in the open field or at the line of scrimmage. Open field impacts were defined as those that occurred outside of the zone where the offensive linemen were positioned at the snap. Line of scrimmage impacts occurred within this zone.

Beyond this categorization, high magnitude practice and game impacts were classified based on the impacted player's role on the play in which the high magnitude impact occurred. Four groupings were created that represented possible causes of impact for players: Blocked, Blocker, Tackled, and Tackler. Blocked refers to impacts in which the impacted player was blocked by an opposing player. Blocker refers to impacts in which the impacted player blocked an opposing player. Tackled refers to impacts in which the impacted player was tackled by an opposing player while carrying the ball. And Tackler refers to impacts in which the impacted player tackled an opposing player who was carrying the ball. Seven isolated, high magnitude game impacts were attributed to fumbles. In these impacts, the football was dropped by a player and nearby players dove to the ground to attempt to retrieve the ball. These impacts could not be grouped with any other impact cause and were excluded from analysis.

High magnitude practice impacts were categorized according to the practice activity at the time of impact. Generalized practice activities for the teams in this study consisted of Offense vs Defense, Tackling – No Blocker, Tackling – Blocker, and Blocking.<sup>8</sup> Offense vs Defense represents all practice activity in which a team’s offense and defense opposed each other. This took the form of intra- and inter-squad 11v11 scrimmages, as well as smaller scale (5v5 or 6v6) scrimmages. Tackling – No Blocker consists of drills in which ball carriers and tacklers oppose each other without a blocker present. Tackling – Blocker represents a permutation of the previous drill, with the notable difference that a blocker is present. Lastly, Blocking consists of drills primarily aimed at practicing blocking or block-shedding, skills that simulate work on the offensive or defensive line. These four generalized categories encompassed nearly all of the high magnitude head impacts observed in practice. Six high magnitude practice impacts occurred in unique activities that could not be grouped into the previous categories and were excluded from analysis.

Each player was assigned to one of three position groups, corresponding to their role on the field (Table 1). Youth players generally play both offense and defense at similar positions. Using traditional football positions, offensive lineman and defensive lineman would be considered similar while running backs and linebackers would be considered similar.

**Table 3.1: Player position groupings. Each player was assigned a position classification according to their role on offense and defense.**

<b>Classification</b>	<b>Positions</b>
<b>Backs</b>	<b>Quarterback, running back, and linebacker</b>
<b>Line</b>	<b>Offensive and defensive line</b>
<b>Perimeter</b>	<b>Wide receiver, cornerback, and safety</b>

The number of high magnitude impacts and impact rates were compared between games, practice as a whole, and specific practice drills. Using video from practices and games, the amount of time spent participating in each practice drill or games was determined. Because the amount of time spent in each activity and the number of impacts differed between the teams and between practices and games, impact rates, measured in high magnitude impacts per hour, were used for comparisons. Byar's method was used to develop 95% confidence intervals for the impact rates in this study. This method retains accuracy for both large and small counts, which were an aspect of this study.<sup>3</sup> Impact rates were determined for each team for open field and line of scrimmage impacts, different causes of impacts, and for different football activities (i.e. practice drills, overall practice, and games). Statistical significance for differences in impact rates was defined by non-overlapping 95% confidence intervals. For each practice drill, ANCOVA was used to determine the effect of the factors position and team on high magnitude head impact exposure, while controlling for the continuous covariates of age, weight, and number of practices. A log transformation of high magnitude impact counts was used to satisfy the assumption of normality, no interactions were assumed, and Type II sums of squares were computed for each factor.

## **RESULTS**

A total of 7590 impacts were recorded and verified, 2057 of which occurred in games. Among all impacts, 571 (8%) exceeded 40 g and were considered to be high magnitude. These high magnitude impacts were comprised of 381 (67%) practice impacts and 190 (33%) game impacts (Table 2). Game impacts exceeding 40 g represented approximately the top 10% of all game impacts for players in this study. Among game impacts, 114 were classified as open field impacts, with the remaining 76 as line of scrimmage impacts. Among practice impacts, 263 were open field impacts and 118 were line of scrimmage impacts. Offense vs Defense had a similar

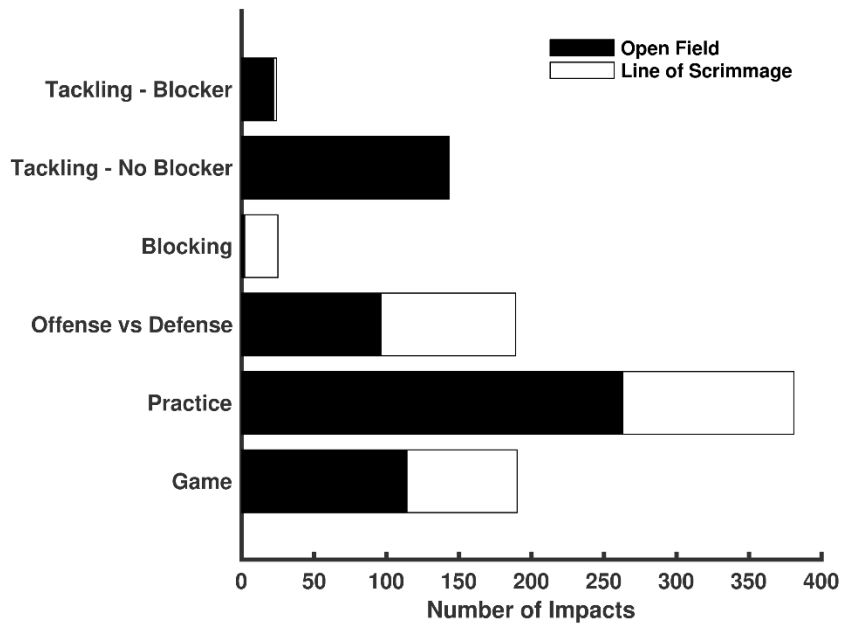
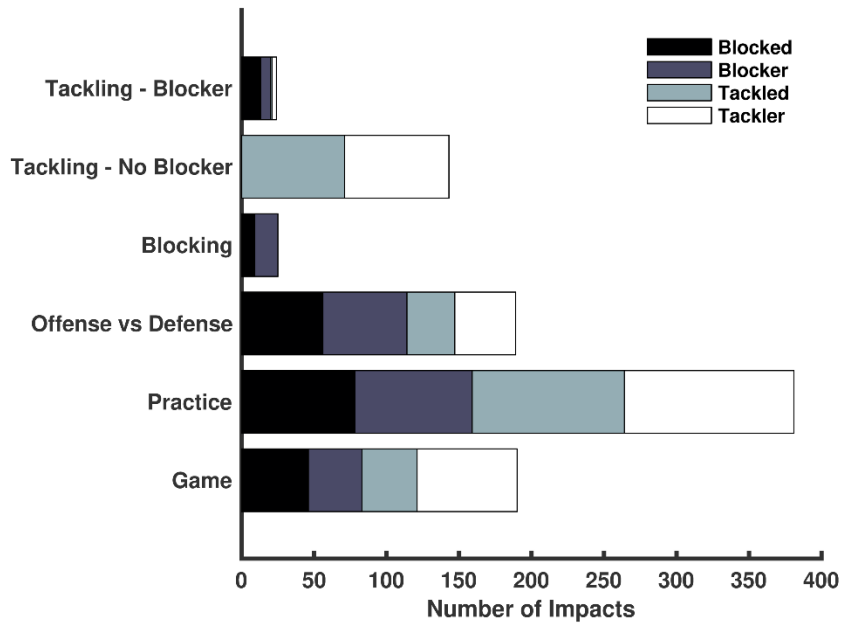
number of impacts to games. Practice drills varied in the breakdown of open field and line of scrimmage impacts, as well as in terms of impact cause (Figure 1).

Differences between the two teams were observed for high magnitude impacts. Juniors had 65 high magnitude head impacts (37%) in 7 games and 113 in 25 practice sessions, while Seniors had 125 (32%) in 7 games and 268 in 30 practice sessions. Juniors experienced 62 open field impacts (33%) and 126 line of scrimmage impacts. Seniors experienced 315 open field impacts (80%) and 78 line of scrimmage impacts.

**Table 3.2: Summary of high magnitude head impact exposure by team. A) Seniors and B) Juniors. The number of high magnitude head impacts varied between activity, team, and position. Players who played more in games generally experienced a higher number of high magnitude impacts in games.**

Subject ID	Team	Position	# Games	# Plays	Game Impacts	# Practice	Blocking Impacts	Offense vs Defense Impacts	Tackling – No Blocker Impacts	Tackling - Blocker Impacts
1	Senior	Line	7	101	0	28	0	3	4	0
2	Senior	Perimeter	6	8	0	10	0	0	0	0
3	Senior	Back	7	457	25	28	0	18	14	8
4	Senior	Back	7	312	1	21	0	7	15	2
5	Senior	Back	5	110	1	9	0	1	3	0
6	Senior	Back	7	460	31	30	2	32	27	5
7	Senior	Line	6	389	5	28	0	6	1	1
8	Senior	Line	7	338	2	29	0	6	14	1
9	Senior	Back	6	351	9	27	0	4	8	0
10	Senior	Line	6	397	2	29	0	2	2	0
11	Senior	Line	6	256	2	25	0	0	3	0
12	Senior	Perimeter	7	75	1	27	0	3	3	0
13	Senior	Line	6	395	20	27	2	4	6	0
14	Senior	Perimeter	3	25	0	14	0	2	5	0
15	Senior	Perimeter	1	7	0	5	0	1	1	0
16	Senior	Line	5	320	1	27	0	0	1	1
17	Senior	Back	7	483	18	28	0	12	14	0
18	Senior	Back	4	122	2	16	0	11	9	4

Subject ID	Team	Position	# Games	# Plays	Game Impacts	# Practice	Blocking Impacts	Offense vs Defense Impacts	Tackling – No Blocker Impacts	Tackling - Blocker Impacts
19	Junior	Line	7	176	1	21	0	1	0	0
20	Junior	Perimeter	6	33	0	21	0	0	0	0
21	Junior	Perimeter	5	187	0	22	0	3	0	0
22	Junior	Back	6	351	11	24	0	3	2	0
23	Junior	Perimeter	7	18	0	22	0	2	2	1
24	Junior	Line	6	315	3	24	3	5	0	0
25	Junior	Back	5	231	2	21	0	2	0	0
26	Junior	Line	7	311	12	22	8	12	0	0
27	Junior	Line	7	86	2	18	1	2	0	0
28	Junior	Line	7	368	10	23	4	12	0	0
29	Junior	Perimeter	5	36	0	14	0	0	0	0
30	Junior	Line	3	39	0	7	0	0	0	0
31	Junior	Perimeter	6	50	0	17	0	0	0	0
32	Junior	Perimeter	6	108	0	22	1	2	0	0
33	Junior	Perimeter	6	109	2	21	0	3	2	0
34	Junior	Line	6	41	1	24	2	1	0	0
35	Junior	Back	7	364	11	24	0	2	5	1
36	Junior	Line	3	93	0	22	1	5	0	0
37	Junior	Perimeter	7	92	0	23	0	1	1	0
38	Junior	Perimeter	3	9	0	18	0	0	0	0
39	Junior	Back	7	271	0	22	0	2	0	0
40	Junior	Line	6	33	2	23	1	11	0	0
41	Junior	Line	5	178	4	21	0	3	0	0
42	Junior	Back	6	165	0	22	0	3	1	0
43	Junior	Line	5	212	0	15	0	0	0	0
44	Junior	Back	3	99	4	17	0	1	0	0
45	Junior	Back	3	40	0	14	0	1	0	0



**Figure 3.1: High magnitude impacts by cause and part of field. Specific practice activities and games differed in the proportion of impact causes (top) and open field impacts (bottom).**

### *High Magnitude Head Impact Exposure in Games*

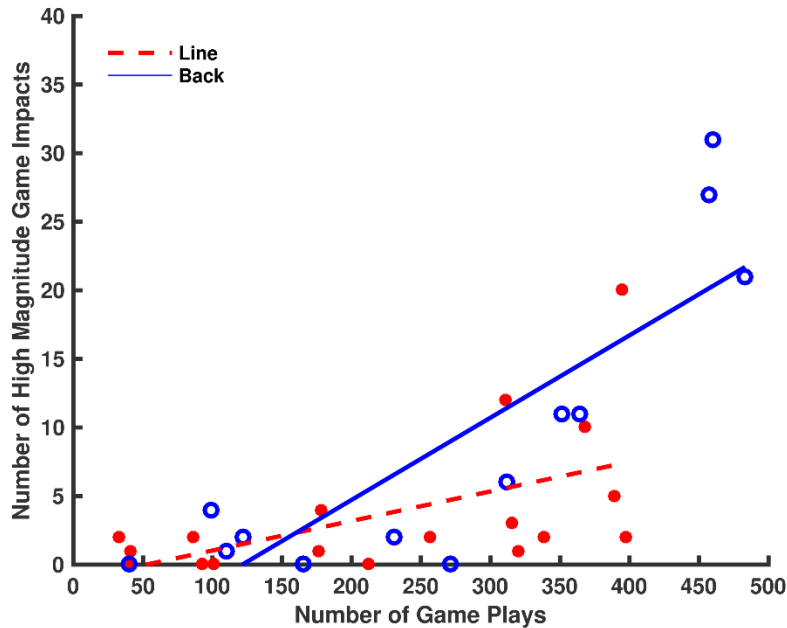
Most high magnitude head impacts occurred for players in the Backs group (Table 3). On average, these players had the most playing time and experienced high magnitude impacts at a higher rate. Increased playing time was associated with an increase in high magnitude head impacts (Line:  $R^2 = 0.304$ ,  $p = 0.0176$ ; Back:  $R^2 = 0.724$ ,  $p = 0.0001$ ). The average Back player participated in 273 plays and experienced 9 high magnitude head impacts, while the average Line player participated in 225 plays with 4 high magnitude head impacts (Figure 2).

**Table 3.3: Summary of game impacts by position. On average, backs were utilized most frequently and experienced the most high magnitude head impacts. Non raw count data are reported as Average (Standard Deviation).**

	<b>Backs</b>	<b>Line</b>	<b>Perimeter</b>
<b># of Players</b>	<b>14</b>	<b>18</b>	<b>13</b>
<b>Total # of Plays</b>	<b>3816</b>	<b>4048</b>	<b>757</b>
<b>Average # of Plays</b>	<b>273 (147)</b>	<b>225 (134)</b>	<b>58 (54)</b>
<b># of Impacts</b>	<b>994</b>	<b>929</b>	<b>157</b>
<b>Impacts Per 100 Plays</b>	<b>26.0 (14.1)</b>	<b>22.9 (13.5)</b>	<b>20.7 (12.4)</b>
<b>Impacts &gt; 40g</b>	<b>120</b>	<b>67</b>	<b>3</b>
<b>Impacts Over 40 g Per 100 Plays</b>	<b>3.1 (2.2)</b>	<b>1.7 (1.8)</b>	<b>0.4 (0.6)</b>

Overall, a majority (60.0%) of game impacts were observed to occur in the open field. Juniors only experienced 28 open field impacts, compared to 37 line of scrimmage impacts. Seniors experienced 86 open field impacts and 39 line of scrimmage impacts. Impact cause was related to a player's position, in that Line players experienced a greater proportion of impacts related to blocking (Blocker or Blocked) while Back players experienced a greater proportion

related to tackling (Tackler or Tackled). Most game impacts for Juniors (61.5%) were associated with blocking while tackling impacts (65.6%) represented the majority for Seniors.



**Figure 3.2: Comparison of game plays to high magnitude impacts. Backs participated in more plays than Line players and experienced more high magnitude head impacts. Filled circles: Line; Open circles: Back.**

*Comparison of High Magnitude Head Impact Exposure in Practices and Games*

Backs experienced a majority of high magnitude impacts related to tackling (72.3%) while Line players experienced most impacts due to blocking (70.9%) (Table 4). Line players experienced most high magnitude head impacts at the line of scrimmage (66.3%) while Back players generally experienced impacts in the open field (82.6%). This was observed to be true for both teams for both games and practices. Line players on Juniors tended to have high magnitude head impacts associated with blocking (92.5%) while a majority of practice impacts for Line players on Seniors were tackling-related (55.1%).

Both teams experienced higher impact rates in games (Juniors 95% CI: 6.2-10.2 impacts/hr and Seniors 95% CI: 12.2-17.5 impacts/hr) relative to the overall practice (Juniors 95% CI: 2.5-3.6 impacts/hr and Seniors 95% CI: 3.9-5.0 impacts/hr) (Figure 3). For line of scrimmage impacts in games, the two teams did not differ in impact rate (Juniors 95% CI: 3.2-6.3 impacts/hr and Seniors 95% CI: 3.3-6.3 impacts/hr). However, Seniors experienced a higher rate of open field game impacts (95% CI: 8.1-12.5 impacts/hr) than Juniors (95% CI: 2.3-5.0).

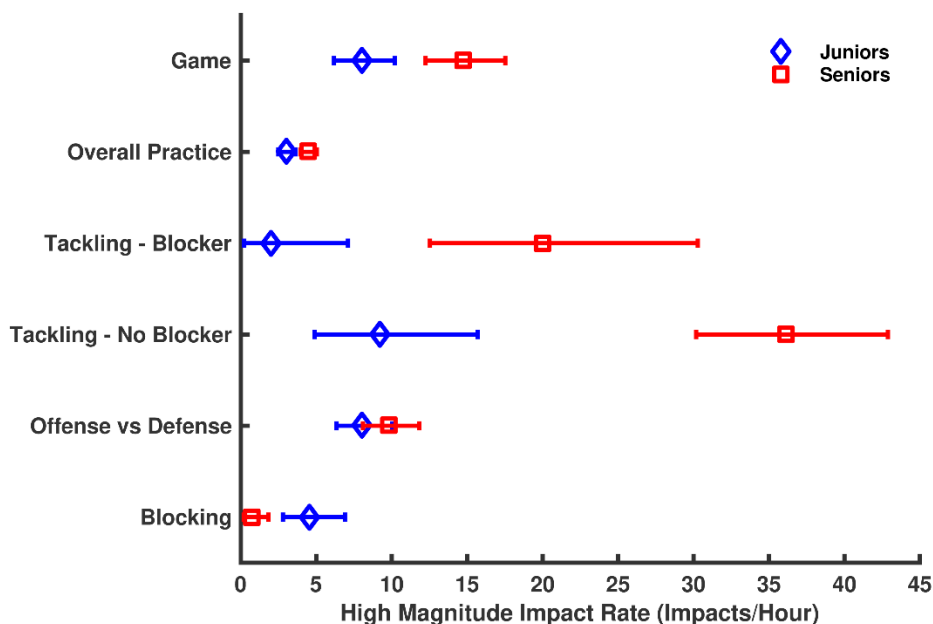
**Table 3.4: Summary of high magnitude impacts by position. Most impacts were observed to occur in the open field. The two teams in this study experienced similar numbers of impacts related to blocking.**

		Games		Practice	
		Tackling	Blocking	Tackling	Blocking
Backs	Open Field	90	6	138	46
	Line of Scrimmage	2	22	15	20
Line	Open Field	13	2	38	13
	Line of Scrimmage	0	52	6	72

The percentage of all impacts that were high magnitude was determined for both teams and session types. Seniors had a higher percentage of high magnitude impacts for both practices and games than Juniors. In practice, 4.5% of all impacts for Juniors were high magnitude, while 9.0% of practice impacts for Seniors exceeded 40 g. For games, 6.6% and 11.4% of impacts for Juniors and Seniors respectively were categorized as high magnitude. High magnitude impacts were 47% more likely to occur in a game than in practice for the Juniors (95% CI: 9.8-98.5%), compared to 27% for the Seniors (95% CI: 4.0-55.3%).

### *Comparison of High Magnitude Head Impact Exposure Between Practice Drills and Games*

The Offense vs Defense drill conducted by Juniors resulted in an impact rate (95% CI: 6.3-10.0 impacts/hr) that was consistent with that observed in games (95% CI: 6.2-10.2 impacts/hr). Seniors (95% CI: 12.2-17.5 impacts/hr) experienced nearly double the impact rate in games that Juniors (95% CI: 6.2-10.2 impacts/hr) experienced. Tackling – No Blocker (95% CI: 30.2-42.9 impacts/hr) was associated with the highest impact rate of all football activities for Seniors (Figure 3). For the Tackling – No Blocker drill, position ( $p=0.004$ ) and team ( $p<0.0001$ ) had an effect on high magnitude impact exposure. Position explained 15.9% of the variance while team explained 23.1%. For The Tackling – Blocker drill, neither position nor team had an effect on high magnitude impact exposure. Position was observed to have an effect for both Offense vs Defense ( $p=0.030$ ) and Blocking ( $p=0.012$ ), explaining 12.0% and 19.5% of variance respectively. For all drills, differences between individual players explained the majority of variance. No difference between impact rates for tackling drills and games was observed for Juniors, whereas the impact rates for tackling drills for Seniors were as high or higher than games.



**Figure 3.3: Impact rates for all football activities by team. For both teams, games were associated with a higher impact rate than practices. Tackling – No Blocker had the impact rate among all practice drills. Impact rates for Seniors exceeded impact rates for Juniors for most activities.**

## DISCUSSION

Given that youth football practices have been observed to be associated with a higher frequency of high magnitude head impacts, head impact exposure research at the youth level has focused on efforts to limit practice impacts. High magnitude head impacts are associated with the greatest risk for concussion.<sup>27</sup> Knowledge of the specific impact scenarios that most frequently occur in games would allow coaches and leagues to construct practice drills that more effectively mimic these impacts rather than exposing players to more severe impacts than they might experience in a game.<sup>8</sup> While the proportion for high magnitude practice impacts (66%) is low compared to previous youth studies, it should be noted that this has been shown to be team dependent and the average age in this study is older than previous youth teams.<sup>8,10,16</sup> As players age, more high magnitude impacts occur during games than in practices.<sup>10</sup>

### *High Magnitude Head Impact Exposure in Games*

The two teams in this study experienced a similar number of high magnitude line of scrimmage impacts (37 for Juniors and 39 for Seniors), but the proportion of game impacts at the line of scrimmage differed (56.9% for Juniors vs. 31.2% for Seniors). For both teams, Backs experienced the majority of high magnitude game impacts in the open field and Line players experienced a majority at the line of scrimmage. Players in open field impacts are able to reach greater speeds and produce higher magnitude head impacts more frequently. Backs ( $41.5 \pm 6.6$  kg), who participated in the highest number of plays on average, are the most active and athletic among the positions, while the Line ( $52.8 \pm 12.4$  kg) tends to be larger. Players were generally exposed to high magnitude impacts in a manner that was consistent with where they lined up prior to the beginning of the play, which reflects the influence of player position on the incidence of high magnitude impacts (Figure 2).

Each position group was associated with a distinct distribution of impact causes. Line players predominately experienced impacts related to blocking, while Back players experienced more tackling-related impacts. Juniors experienced a majority of its high magnitude game impacts due to blocking. When players are younger, they are more likely to bunch up. It is often more difficult for these players to generate much speed prior to impact, so tackling-related impacts for Juniors players would generally be lower in magnitude. The similar number of blocking impacts between the two teams would suggest that age or style of play does not affect the incidence of high magnitude impacts near the line of scrimmage.

### *Comparison of High Magnitude Head Impact Exposure in Practices and Games*

Regardless of session, Juniors experienced fewer high magnitude head impacts than Seniors. This could be related to any number of factors, such as age, practice structure, or intensity. For both teams, practice was associated with less likelihood of sustaining a high magnitude head impact than games. On Juniors, 1 in 15 game impacts would be high magnitude, while 1 in 9 impacts would be high magnitude for Seniors. Larger and faster players can impact with greater energy than smaller players, which would explain some of the observed differences in high magnitude head impact exposure between the two teams. The practice conducted by Seniors was 2x as likely to produce high magnitude impacts as Juniors' practice. This alludes to increased intensity of Seniors' practice relative to Juniors'. While difficult to quantify, we observed that the intensity of practices on Seniors was noticeably higher than that of Juniors. Practice structure and coaching style could expose players to more situations that result in high magnitude impacts or reward players for making bigger hits, rather than safer hits.

For both teams, the high magnitude impact rate was higher in games than in practice (Figure 3). Practices had more non-contact time than games did, which likely contributed to some of the differences observed. The game style differences between the age groups manifested itself in a higher open field impact rate for Seniors (95% CI: 8.1-12.5 impacts/hr) relative to Juniors (95% CI: 2.3-5.0 impacts/hr). The older players had more experience playing football and were more likely to make plays in the open field. In games and practice, most impacts for Backs were observed to be in the open field and tackling-related, while Line players experienced a majority of line of scrimmage impacts related to blocking. Players were exposed to impact scenarios in practice that were representative of game situations they would experience.

### *Comparison of High Magnitude Head Impact Exposure Between Practice Drills and Games*

Practice sessions lasted 90 minutes for Juniors and 120 minutes for Seniors. On average, 40 minutes of practice for both teams were devoted to warming up or cooling down. The two teams conducted Blocking (11 minutes) and Offense vs Defense (23 minutes) for the same amount of time in an average practice. Juniors did tackling drills, with or without a blocker, for 5 minutes in an average practice, compared to 9 for Seniors (Table 5). The remaining time, 10 minutes for Juniors and 37 minutes for Seniors, were devoted to water breaks, coaching instruction, and position-specific, non-contact drills. Not every drill was done at each practice and the average practice time represents an aggregation over the course of the season.

**Table 3.5: Practice structure by team. Drills that produced high magnitude impacts in practice were conducted for a similar amount of time between the two teams in this study. Seniors conducted 4 additional minutes of tackling drills. Since the number of impacts in practice for Seniors was more than double that of Juniors, the coaching style and practice intensity were likely higher. All numbers reported are minutes.**

	<b>Juniors</b>	<b>Seniors</b>
<b>Tackling – No Blocker</b>	<b>3</b>	<b>7</b>
<b>Tackling – Blocker</b>	<b>2</b>	<b>2</b>
<b>Blocking</b>	<b>11</b>	<b>11</b>
<b>Offense vs Defense</b>	<b>23</b>	<b>23</b>
<b>Warm-up or Cool Down</b>	<b>40</b>	<b>40</b>
<b>All Other Activities</b>	<b>10</b>	<b>37</b>

### *Limitations*

This study had several limitations. For individual measurements, the HIT system is associated with random error up to 15.7%, though the average error is only 1%.<sup>2</sup> Distributions of data were used for analysis throughout this manuscript in an effort to minimize the effects of any

measurement error. Head impact exposure varied among individuals and between the teams in this study and would likely vary were similar analysis conducted with other individuals and teams.<sup>5-8,10,12-17,32,33</sup> The number of players on both teams in this study likely contributed to the play counts determined and would vary by age group and team size. Practice structure and the game-to-practice ratio will also likely vary by age group and by league. Lastly, this analysis was restricted to high magnitude impacts, which are those that are most likely to be visually verified. Analysis considering lower magnitude impacts as well might provide different results, at the expense of certainty regarding the data set and conclusions resulting from the analysis.

### *Conclusions*

Head impact kinematic data were collected from two youth football teams of players 9-12 years old in order to determine where high magnitude head impacts occur in games and ascertain how representative practice is of games. Most impacts were found to occur in the open field. Back players were usually involved in these open field impacts while Line players experienced the majority of line of scrimmage impacts. Though the impact rate was lower in practice than in games for both teams, practices occur more frequently than games do and expose players to a higher number of high magnitude head impacts. The two teams in this study structured their practices similarly, but one team experienced more than double the number of high magnitude practice impacts due to differences in player age, coaching style and intensity. How practice activities are conducted contributes towards the overall high magnitude head impact exposure for practice, not just the practice activity itself. This analysis, augmented by the previously developed practice framework, may be of use to researchers or policy makers seeking to reduce head impact exposure in youth football.

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## **Chapter 4: Postural Control in Youth Football Players: A Comparison of the Balance Error Scoring System and a Force Plate Protocol**

### **ABSTRACT**

Postural control testing is often used by clinicians and athletic trainers to assess the health of athletes during recovery from a concussion. Knowledge of the validity of such testing within a youth population is limited. The objective of this study was to compare the Balance Error Scoring System (BESS) with a force plate protocol and determine their effectiveness in differentiating postural control within a cohort of 34 youth football players (average age of  $9.9 \pm 0.6$  years). Participants completed testing at the beginning and end of the youth football season. Testing consisted of the BESS and a force plate protocol with two tests. There were no significant differences between BESS scores before the season and after the season ( $P = 0.54$ ). Performance on the BESS was not associated with any of the center of pressure (COP) metrics considered in this study. A modified version of the BESS administration that only utilizes tandem stances and a one foot test on a flat surface may be a better discriminator of postural control in youth athletes. A more rigorous force plate protocol involving BESS stances or dual-task interference may be appropriate. It is expected that these modifications would serve as better indicators of postural control for children than the standard testing protocols. Further research is required to determine the viability of postural control testing with this population.

### **INTRODUCTION**

Sports-related concussions have become a public health concern, with as many as 3.8 million occurring annually in the United States.<sup>11,36,67</sup> Biomechanics research regarding football-related concussions has been spurred by data showing football to have the greatest number of concussions.<sup>25</sup> Despite the fact that youth players constitute 70% of the football-playing

population, most research has focused on high school and older populations<sup>4-6,15,45,53,62,64</sup> rather than youth populations.<sup>13,16,50,69,75</sup>

Concussive impacts have been the center of most research as the effect of subconcussive impacts remains largely unknown. Athletes who have suffered a concussion can experience changes in postural control as concussions interfere with the nervous system.<sup>28,41</sup> Return to play protocols for athletes after concussions have become commonplace even though preseason balance testing remains limited.<sup>49,63</sup> In collegiate populations, short-term learning impairments and balance deficits have been observed even for non-concussed players.<sup>38,48</sup>

The most commonly implemented balance testing protocol used by athletic trainers and physical therapists in assessing postural control in athletes is the Balance Error Scoring System (BESS).<sup>28</sup> The BESS is a clinical, static balance assessment that is easy to administer and may be used without instrumented testing devices.<sup>2</sup> The BESS testing protocol is described in the methods section of this manuscript. It has primarily been used to measure postconcussion deficits from sports injuries.<sup>3,28,39,40,60</sup> The BESS has even been shown to differentiate between concussed and healthy youth athletes.<sup>22</sup> The reliability of the overall BESS has been shown to vary considerably while a modified version has shown improved results.<sup>2,7,8,20,22,30,31,42,43,61</sup> Utilization of repeated administration to increase the reliability of the protocol is not recommended as a practice effect has been observed for repeated tests of the BESS, though the magnitude of this practice effect is variable.<sup>14,29,70</sup> Alternatively, a static balance assessment (consisting of eyes open and eyes closed trials), which makes use of an instrumented force plate, utilizing center of pressure (COP) trajectories can be used to assess athlete postural control.<sup>9,10,12,18,19,21,26,32,33,46,47,52,54-56,60,61,66,71,76</sup> This quantitative analysis of balance has been used to delineate between healthy and impaired states for athletes.<sup>9,10,54</sup>

Though both the BESS and force plate protocols have been used extensively in assessing postural control of both healthy and impaired athletes, a comparison between the protocols has yet to be conducted at the youth level. Youth males have been shown to develop postural control later in adolescence, necessitating analysis of commonly used postural control testing protocols.<sup>58,66</sup> The objective of this study was to assess the ability of the BESS and an established force plate protocol to discriminate postural control differences among youth football players. Evaluation of these protocols in the youth population could lead to affirmation of their implementation or prompt development of youth-specific postural control testing.

## **METHODS**

Two teams of 9-11 year old youth football players (average age of  $9.9 \pm 0.6$  years) comprised the subjects for this study approved by the Virginia Tech Institutional Review Board. Players were recruited and provided verbal assent to participation while their guardians provided written consent. Preseason testing was conducted the first week of the season before contact practice began and postseason testing was completed within 2 weeks of the end of the season. The testing consisted of BESS administration and a force platform protocol. Preseason testing was completed by 34 players while 31 players completed postseason testing. One player's testing data was not used as the athlete had a neurological condition (Attention Deficit Hyperactivity Disorder) that could affect postural control. Analysis only considered the 30 players that completed testing at the beginning and end of the season. No player sustained a concussion during the course of the season.

The BESS utilizes three stances: double leg, single leg, and tandem that are tested on both a flat surface and a foam pad. This represents a total of 6 trials, each of which has a 20 second duration and is conducted with the participant's eyes closed.<sup>27</sup> A subscore for each trial is

determined by counting participant errors, with an overall score representing the summation of each trial's score. Errors included opening of the eyes, stepping or falling, removing hands from the hips, abduction or flexion of the hip beyond 30°, lifting of the heel or toes from the testing surface, and failure to return to testing position within 5 second. The maximum possible subscore is 10.

Center of pressure (COP) data were collected using an IsoBALANCE<sup>®</sup>2.0 (IsoTechnology, Australia) force plate. Participants completed two 30 second trials – one with eyes open and the other with eyes closed.<sup>10</sup> Foot placement was consistent among all participants with indicators on the platform. The force plate output COP trajectories at a frequency of approximately 10 Hz in x and y coordinates over the course of the test. The x-axis represents the Medial-Lateral (ML) axis while the y-axis represents the Anterior-Posterior (AP) axis. Similarly to Quatman-Yates et al.,<sup>54</sup> a distinction was made between COP measures of path characteristics and data structure characteristics. Path characteristics are metrics that represent the amount of variability within the data, while data structure characteristics capture patterns of variability within the data. Path characteristics have been summarized in Table 4.1. Path characteristic metrics are inherently similar, which can make it difficult to differentiate among the various metrics.<sup>9,54</sup>

**Table 4.1: Summary of path characteristics and method of calculation. Path characteristics depend on each other.**

<b>Metric</b>	<b>Description</b>	<b>Equation</b>
<b>Sway AP</b>	<b>Standard deviation of movement in AP direction</b>	$S_{AP} = \sqrt{\frac{\sum_{i=1}^N (AP_i - \overline{AP})^2}{N - 1}}$
<b>Sway ML</b>	<b>Standard deviation of movement in ML direction</b>	$S_{ML} = \sqrt{\frac{\sum_{i=1}^N (ML_i - \overline{ML})^2}{N - 1}}$
<b>Path Length</b>	<b>Total distance traveled during trial</b>	$PL = \sum_{i=2}^N \sqrt{(AP_i - AP_{i-1})^2 + (ML_i - ML_{i-1})^2}$
<b>Maximum Path Velocity</b>	<b>Max velocity during trial</b>	$MPV = \frac{\sum_{i=1}^N (PL_{i+1} - PL_i)}{t_{i+1} - t_i}$
<b>COP Area</b>	<b>95% confidence ellipse area</b>	$2\pi F_{.05,2,N-2} (S_{AP}^2 S_{ML}^2 - S_{AP-ML}^2)$ $S_{AP-ML}$ is the covariance between the AP and ML directions.

Recently, various measures of the entropy of the COP trajectory have been utilized to further characterize the postural data.<sup>21,23,34,44,54,56,57,65</sup> Entropy measures the overall variability or randomness of a particular data series and is considered as a data structure characteristic. A lower entropy value would be indicative of a less varied balance trajectory. This dual approach, including both path and data structure characteristics, provides an overall description of the postural stability of each participant. Four measures of data entropy were generated for each test: AP, ML, Renyi, and Shannon Entropy.<sup>10,23,35,56</sup>

AP and ML Entropy are calculations of sample entropy and represent the variability of the COP trajectory as it relates to each direction respectively. Sample entropy is determined by comparing a given data vector template from the COP trajectory to all other vectors within the trajectory and counts all those that are within a defined similarity range. A more comprehensive

description regarding the algorithm for determining sample entropy is available.<sup>34,59</sup> Parameter selection for this analysis was conducted as specified by Lake et al.<sup>35</sup>

Renyi and Shannon Entropy represent variability in the overall COP trajectory and are determined through graphical representation of the trajectory. A grid is developed that contains subunits that are equal in length and height to the standard deviation in the ML and AP directions respectively. Then, the number of points in the trajectory found within each subunit are determined in order to calculate the probability of COP coordinates residing in a particular subunit. Using this probability, Shannon Entropy is defined as follows:

$$\text{Shannon Entropy} = - \sum_{i=1}^m p_i \ln p_i$$

where  $p_i$  represents the probability of COP coordinates residing in a specific subunit of the  $m$  overall subunits.<sup>23</sup> A data set that resides entirely within a single subunit would intuitively result in a Shannon Entropy of 0. Renyi Entropy represents the generalized form of Shannon Entropy and utilizes the same methodology. It is calculated as follows:

$$\text{Renyi Entropy} = \frac{1}{1-q} \ln \left( \sum_{i=1}^m p_i^q \right)$$

where  $q$  is a selected parameter and is equal to -1 for this analysis.<sup>54</sup>

BESS subscores were compared with the overall BESS score to determine the correlation of each trial to the total score. Each of the path and data structure characteristics were similarly compared within their group. Comparisons between the two protocols were then conducted to determine if there was an association between BESS subscores and force plate metrics. Potential differences between preseason and postseason data were investigated, as well as overall differences between the test methods. Coefficients of determination were calculated for each of the above comparisons to quantify the ability of the metrics to predict postural stability.

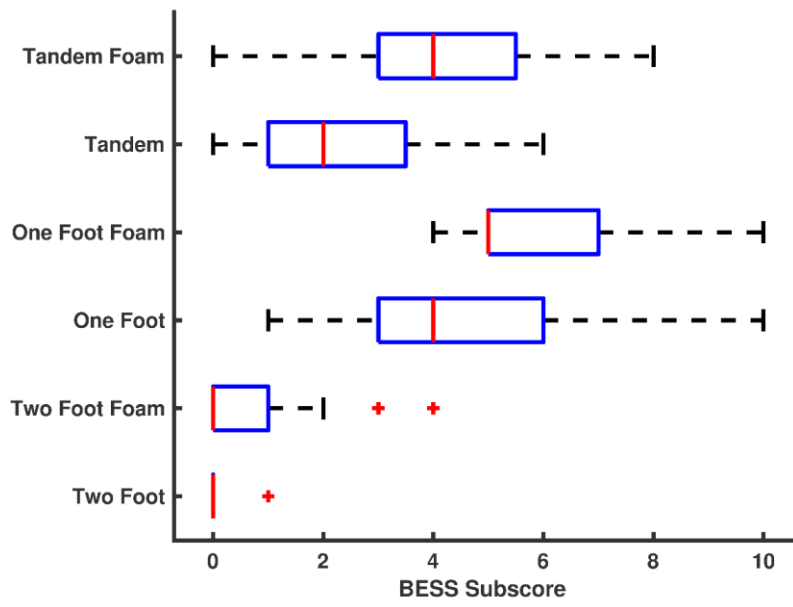
Differences between preseason and postseason data, as well as eyes open and eyes closed force plate data, were assessed using a paired t-test with a level of significance defined for  $\alpha < 0.05$ .

## RESULTS

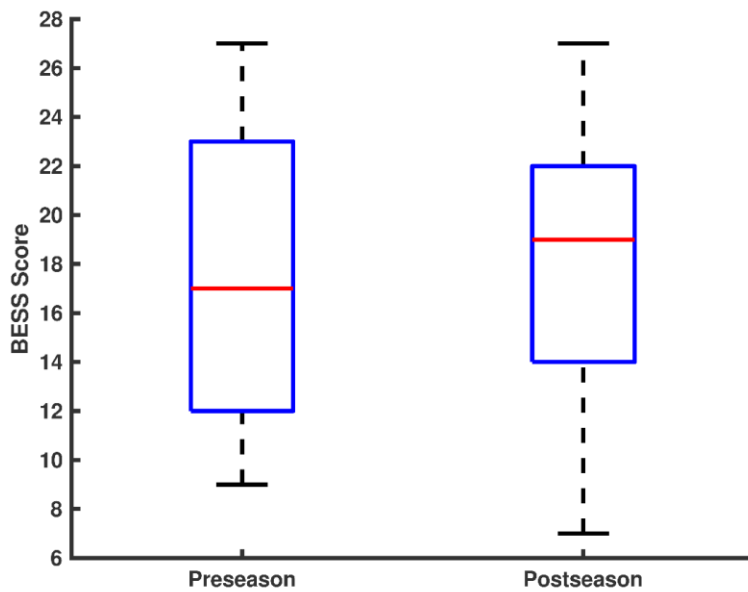
The BESS protocol detected no significant difference between preseason and postseason testing for the overall score ( $P = .54$ ). Both two-foot tests resulted in very few errors while the one-foot test conducted on a foam surface resulted in a large amount of errors for most participants (Figure 4.1). Further, these tests explained low amounts of variance in the overall score (Table 4.2). Though no overall differences were observed between preseason and postseason BESS scores, individual athletes' scores varied (Figure 4.2).

**Table 4.2:  $R^2$  values by BESS stance.  $R^2$  values against total score were observed to be lowest for the two foot stances. Though the tandem flat and one foot foam tests had the same  $R^2$  value, greater variability was observed in the tandem flat stance.**

<i>Coefficients of Determination</i>		<i>Total Score</i>
<i>Flat</i>	Two Foot	0.00
	One Foot	0.61
	Tandem	0.36
<i>Foam</i>	Two Foot	0.24
	One Foot	0.36
	Tandem	0.53



**Figure 4.1: Number of errors by BESS stance. Two foot stances resulted in minimal errors while the one foot test performed on foam was saturated in a high amount of errors. Greater variability was observed for both tandem stances, as well as the one foot stance on a flat surface.**

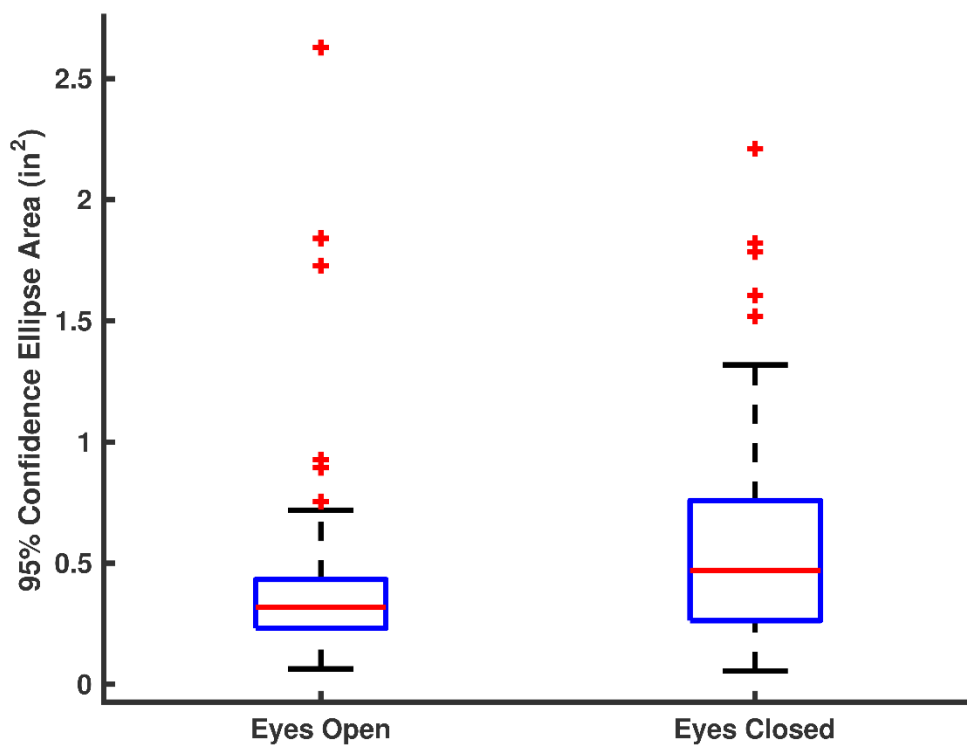


**Figure 4.2: Overall BESS score by test date. Preseason and postseason BESS scores were found to not differ. Individual subject variability was present.**

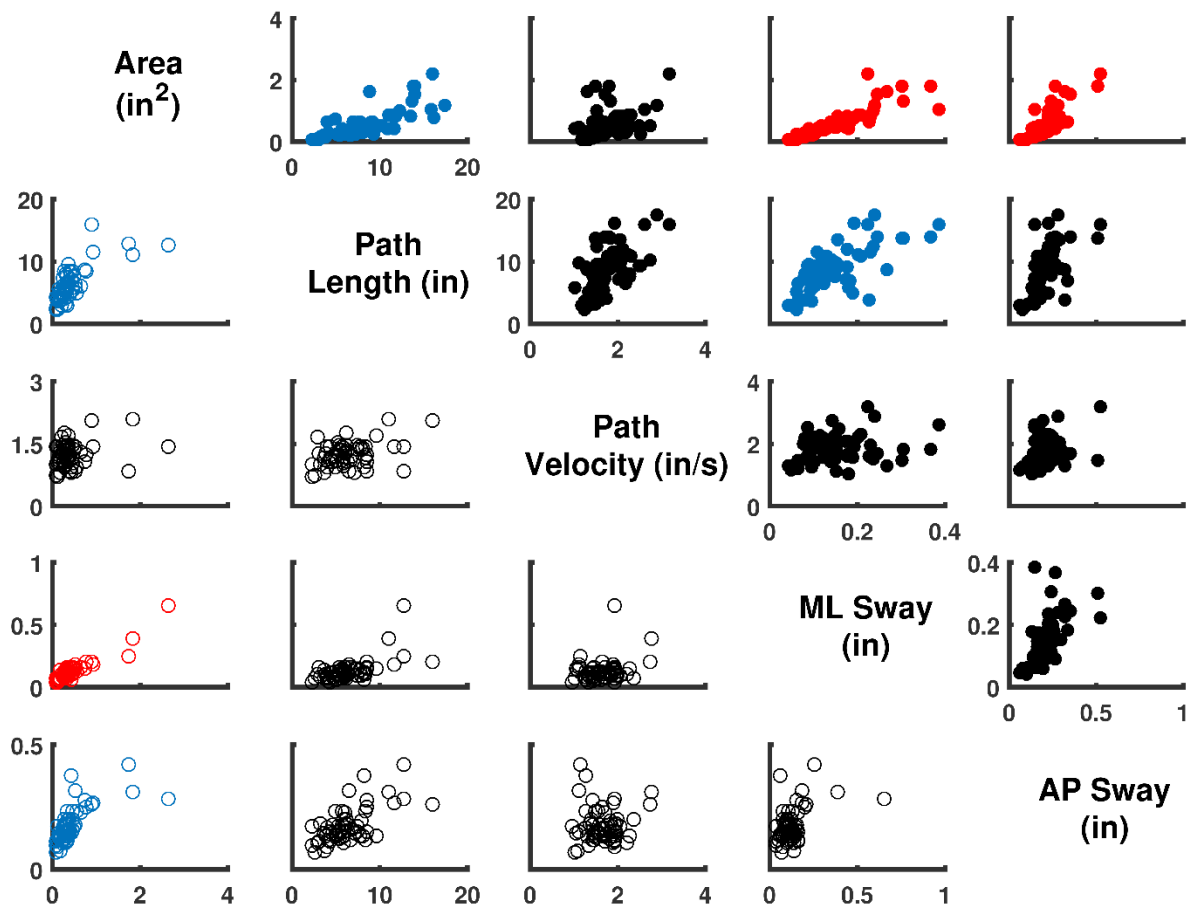
The force plate protocol consisted of two trials (eyes open and eyes closed) and two time points (preseason and postseason). The average and standard deviation for each metric is reported in Table 4.3. The eyes open and eyes closed trials were found to be significantly different for AP and ML Entropy, as well as each of the path characteristics except for ML Sway ( $P < 0.05$ ). Greater subject variability was observed in the eyes closed trial than in the eyes open trial (Figure 4.3). Similar to the BESS, preseason and postseason data were not detected to be significantly different ( $P > 0.05$ ). Related metrics were found to have higher coefficients of determination (Table 4.1 and Figure 4.4). Individual variances, both negatively and positively, for athletes between preseason and postseason tests were present. Some athletes performed better in the preseason than in the preseason while others experienced the opposite effect.

**Table 4.3: COP metrics for force plate analysis. Significant difference was detected between eyes open and eyes closed tests for all metrics except ML Sway, Renyi Entropy, and Shannon Entropy. Preseason and postseason tests were observed to be similar. Mean (Standard Deviation)**

	Preseason		Postseason	
	<i>Eyes Open</i>	<i>Eyes Closed</i>	<i>Eyes Open</i>	<i>Eyes Closed</i>
<i>AP Sway (in)</i>	0.13 (0.07)	0.16 (0.08)	0.13 (0.11)	0.14 (0.07)
<i>ML Sway (in)</i>	0.19 (0.07)	0.21 (0.09)	0.17 (0.07)	0.22 (0.09)
<i>Path Length (in)</i>	6.71 (3.35)	9.30 (4.34)	6.12 (2.10)	8.60 (3.43)
<i>Max Path Velocity (in/s)</i>	1.72 (0.44)	1.86 (0.42)	1.66 (0.35)	1.79 (0.48)
<i>95% Ellipse Area (in<sup>2</sup>)</i>	0.48 (0.44)	0.67 (0.49)	0.40 (0.44)	0.59 (0.49)
<i>Renyi Entropy</i>	3.44 (0.27)	3.54 (0.33)	3.53 (0.24)	3.49 (0.35)
<i>Shannon Entropy</i>	2.52 (0.15)	2.52 (0.14)	2.48 (0.20)	2.51 (0.18)
<i>AP Entropy</i>	0.34 (0.11)	0.45 (0.10)	0.33 (0.09)	0.42 (0.11)
<i>ML Entropy</i>	0.32 (0.10)	0.37 (0.11)	0.31 (0.08)	0.36 (0.11)



**Figure 4.3: Comparison of eyes open and eyes closed force plate trials. Subjects generally performed well during the eyes open trial. Lower performances and greater subject disparity were observed during the eyes closed trial.**



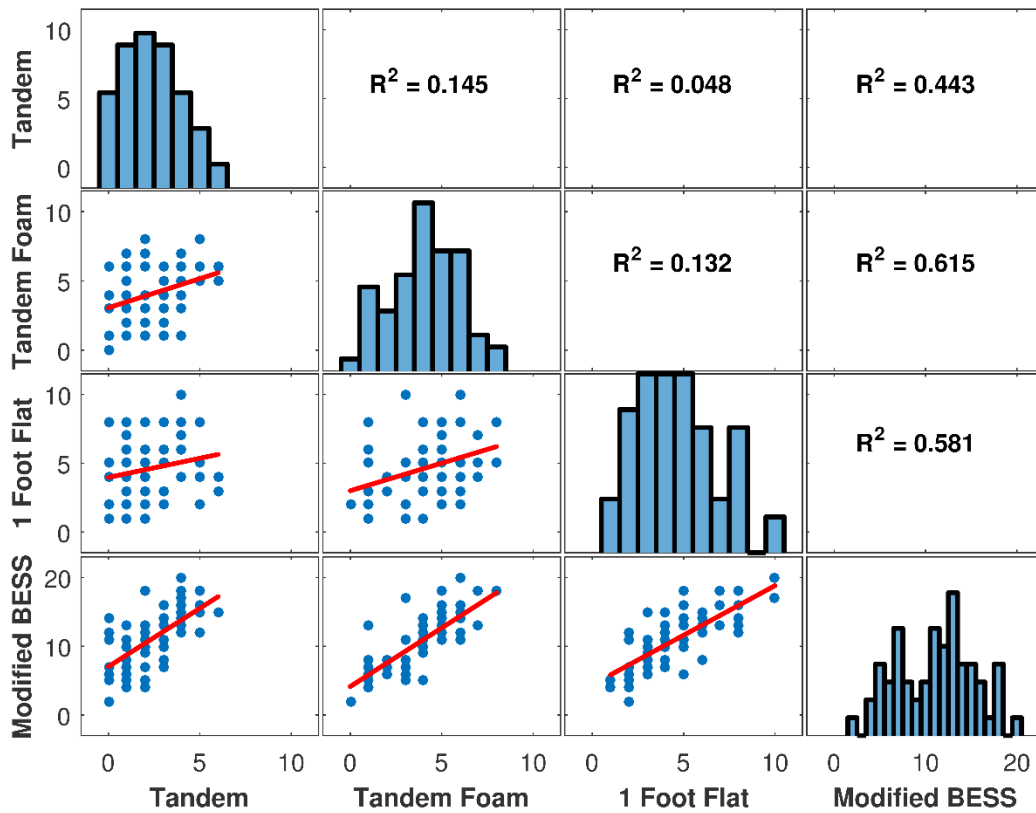
**Figure 4.4: Correlation between path metrics. Open circles represent Eyes Open trials. Closed circles represents Eyes Closed trials. Black markers are for  $R^2$  values below 0.5. Blue markers are for  $R^2$  values between 0.5 and 0.6. Red markers are for  $R^2$  values exceeding 0.6. Dependent metrics are generally associated with greater  $R^2$  values.**

Since differences between preseason and postseason testing for both the BESS and force plate protocol were not detected, the data were combined into one pool for the purposes of assessing the correlation of the BESS and force plate metrics. Distinction was made between eyes open and eyes closed trials in assessing correlation between the two testing protocols. Performance on the BESS was found to not be tied to performance on the force plate protocol. The number of errors for each trial of the BESS was compared to both path and data structure characteristics from

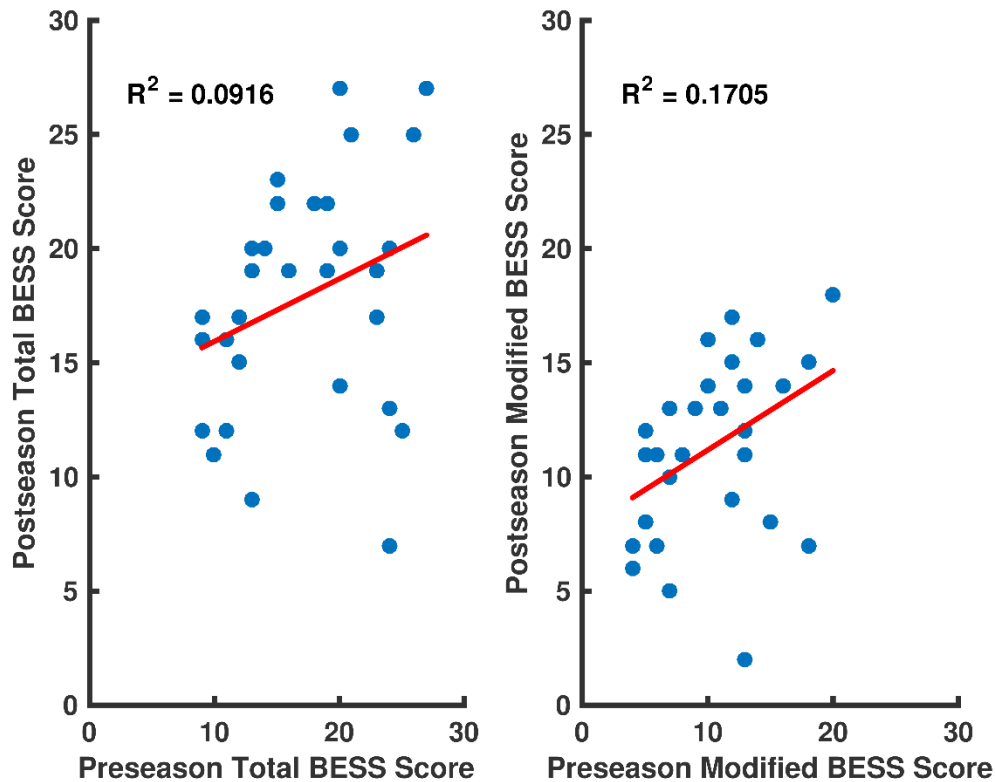
the force plate protocol to determine correlation. No correlation between the test methods was observed ( $R^2$  values ranged from 0-0.1).

## **DISCUSSION**

The average number of total BESS errors reported in this study was greater than that reported in adult populations.<sup>2</sup> Both of the two foot trials resulted in less than one error on average (Figure 4.1). These trials were not challenging enough for the participants in this study. A modified BESS protocol has been previously presented that eliminates the use of the two footed trials.<sup>31</sup> These trials were eliminated as they were associated with low variance, not inversely tied to exertion or fatigue, and were found to not differentiate concussed and healthy athletes.<sup>61,68,70,72</sup> The one foot trial performed on a foam pad resulted in the highest average error ( $5.9 \pm 1.5$ ) among all trials and was consistent with previous research.<sup>22,61</sup> This trial was saturated with errors, clouding the overall results. Athletes struggled to maintain balance throughout the trial. In select cases, athletes took extended periods of time to return to the testing stance, leading to fewer errors. The effectiveness of this stance could not be determined as a result. Considering the limited variance between subjects on each of the two foot trials and the one foot trial on a foam pad, we hypothesize that a youth-specific BESS administration consisting of only both tandem trials and the one foot trial on a flat surface would best characterize postural stability (Figure 4.5). These tests were observed to have the greatest variance among this healthy cohort of youth football players and would be more likely to detect postural control differences (Figure 4.6). Stances with greater variance between subjects would allow for better discrimination of postural control both between and within subjects. For an athlete with a concussion, it has been shown that performance on the BESS has decreased for a period of time following the injury.<sup>3,27,28,31,39,40,63</sup>



**Figure 4.5: Correlation of BESS stances with recommended BESS protocol. The tests that make up the modified BESS represent a greater amount of variation in the total score than the tests that were excluded (two foot flat, two foot foam, and one foot foam). These tests have a wider range of values among participants in this study.**



**Figure 4.6: Comparison of BESS protocol and the BESS protocol recommended by this study. The Modified BESS protocol proposed in this study would better explain variability between preseason and postseason testing than the standard BESS protocol.**

The force plate protocol confirmed a difference between the eyes open and eyes closed tests in terms of path characteristics. This is consistent with suggestions from the literature.<sup>10</sup> Most all athletes performed well in the eyes open test while a greater disparity in metrics existed in the eyes closed test (Figure 4.3). For this study, entropy measurements were not able to differentiate athletes as the results were largely similar with limited variation from athlete to athlete. Path characteristic metrics were observed to vary considerably more and thus be better differentiators of postural control in this population. Selection of an optimal path metric for assessment of postural control is confounded by the linked nature of the parameters (Figure 4.4).

For instance, the 95% confidence ellipse area is calculated by using the sway in the anterior-posterior and medial-lateral directions. No path metric is recommended over another for this testing protocol. Other studies have shown various entropy measurements to differentiate postural control in youth populations.<sup>10,23,54</sup> These studies utilized the eyes open and eyes closed protocol from this study but for a two minute duration instead of the 30 seconds implemented here. The two minute duration has been observed to maximize the detection of COP changes due to concussion.<sup>23</sup> Over a longer duration, variation in the COP trajectory would become more pronounced amongst subjects. A longer duration test could also potentially result in measurements of non-stable COP trajectories that would prevent use of the path characteristic metrics presented in this study.<sup>33</sup> Entropy measurements may still be a viable discriminator within this population.

For both the BESS and force plate protocols, no overall differences between preseason and postseason data were observed. This finding is consistent with previous research, in that a single season of football may not result in postural control differences.<sup>38,49</sup> Individual athletes exhibited differences between the two test sessions. These differences could stem from fatigue or drowsiness, learning effects, or improved balance from consistent physical activity (i.e. a season of football).<sup>30,43,48,68,70,72</sup>

No correlation was observed between the force plate protocol and the BESS. Greater differences between subjects were found with the BESS than with the force plate. Utilizing a different force plate protocol might provide some agreement between force plate metrics and BESS scores. Studies utilizing the eyes open and eyes closed protocol have supplemented it with a dual task interference component to add a degree of difficulty to the test.<sup>1,17,73,74</sup> To further assess the ability of the BESS to serve as an effective tool for assessing postural control, a force plate protocol

that makes use of BESS positioning may also be useful. For instance, it would be expected that an eyes open tandem or one foot trial would result in a greater disparity among test subjects for most metrics while not presenting an impossible task.

No subjects in this study experienced a concussion so the effectiveness of the BESS and a force plate protocol within an injured population could not be considered. The reliability of the BESS in adult populations has been shown previously to be limited. Further, postural control development in youth populations, specifically males, is limited.<sup>24,37,51,66</sup> Thus, differences in BESS scores among athlete may be more indicative of developmental differences than of postural control differences. A modified BESS protocol was suggested that could serve to more effectively differentiate the postural control of healthy youth subjects. As studies have shown concussed athletes to show poorer balance than their healthy counterparts, this modified BESS could also increase the efficacy of the test. Further, a limited force plate protocol was utilized in this study. A more challenging series of tests would likely be more effective at detecting postural control differences. This more challenging force plate protocol may lead to subjects having to reset their balance within a trial. Multiple trials would likely be used to mitigate this effect.

Two youth football teams of players 9-11 years old completed preseason and postseason postural control testing that consisted of administration of the BESS and a force plate protocol. A modified BESS test was proposed that could better differentiate athletes' postural control. Path and data structure characteristics may both be effective in assessing postural control within this population but the test duration and positioning must be considered. The use of postural control testing in a youth population may be viable, with the suggested alterations outlined in this study. Further research exploring the effectiveness of these modifications is necessary.

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## **Chapter 5: Closing Remarks**

### **RESEARCH SUMMARY**

The research presented in this thesis investigated head impact exposure in youth football. Utilizing previously validated data collection techniques, innovative methods of analysis were employed in each study included in this thesis. By instrumenting youth football helmets with accelerometers for each game and practice over two seasons, a large dataset of youth football head accelerations was obtained. By analyzing high magnitude head impacts in youth football practices and games, insight into potentially risky football activities was gleaned. The methodologies of each study can be implemented by future groups and organizations to develop larger and more representative datasets for youth football. These data would have the capacity to affect future youth football rules and regulations.

The balance study assessed two commonly used baseline/return to play protocols for athletes. Current balance assessments were observed to fall short for detecting postural control differences in this youth population. The resulting analysis may ultimately be used in the development of a youth-specific balance assessment that can detect differences in postural control among youth populations that current assessments do not.

## PUBLICATION OUTLINE

All research presented in this thesis will be published in scientific journals or presented at national biomedical engineering conferences. Table 5.1 outlines the journal or conference where each chapter will be presented.

**Table 5.1: Publication plan for research from this thesis.**

<b>Chapter</b>	<b>Title</b>	<b>Journal/ (Conference)</b>
<b>2</b>	<b>Drill-specific Head Impact Exposure in Youth Football Practice</b>	<b>Journal of Neurosurgery: Pediatrics* (SB<sup>3</sup>C &amp; BMES Annual Meeting)*</b>
<b>3</b>	<b>High Magnitude Head Impact Exposure in Youth Football</b>	<b>Journal of Neurosurgery: Pediatrics (SB<sup>3</sup>C)*</b>
<b>4</b>	<b>Postural Control in Youth Football Players: A Comparison of the Balance Error Scoring System and a Force Plate Protocol</b>	<b>Journal of Applied Biomechanics#</b>

\*Accepted #Submitted