Identifying High Risk Individuals in Youth Football and Evaluating Tackling Technique

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ACADEMIC ABSTRACT

Nearly 3.5 million kids play youth football every year in the United States, many in independent organizations with few or no rules for limiting head impact exposure in practices or competition. Studies have found potential long-term effects of repetitive head impact exposure from a young age, even in the absence of concussion. The best methods for reducing head impact exposure include a multi-pronged approach: limiting contact through rules changes, teaching proper technique for contact, and designing equipment with better protective capabilities.

Four youth football teams were studied for one season each using helmet mounted accelerometer arrays. The instrumentation measured all head accelerations the athletes experienced above a 10 g threshold. Head acceleration data indicated that youth teams often have a small subset of players who account for a disproportionately large number of high-risk (>40 g) head impacts. As few as six players (6%) accounted for over 50% of all high-risk impacts seen in practice sessions. Technique used during tackling and tackle-absorption had considerable effect on head acceleration experienced. Both the tackler and ball carrier were found to be at greater risk for high magnitude head impacts when exhibiting poor form as defined by specific tackling recommendation criteria.

These data suggest that individualized interventions encouraging proper form, especially for a subset of impact-prone players, may be beneficial in reducing high magnitude head impact exposure for an entire youth football team. This is especially critical because a majority of high-risk impacts are experienced in practice at the youth level.

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GENERAL AUDIENCE ABSTRACT

Nearly 3.5 million kids play youth football every year in the United States, many in independent organizations with few or no rules for limiting head impact exposure in practices or competition. Studies have found potential long-term effects of repetitive head impact exposure from a young age, even in the absence of concussion. The best methods for reducing head impact exposure include a multi-pronged approach: limiting contact through rules changes, teaching proper technique for contact when it does occur, and designing equipment with better protective capabilities.

Four youth football teams were studied for one season each using helmet mounted accelerometer arrays. Head acceleration data indicated that youth teams often have a small subset of players who account for a disproportionately large number of high-risk head impacts. As few as six players (6%) accounted for over 50% of all high-risk impacts seen in practice sessions. Technique used during tackling and tackle-absorption had considerable effect on head acceleration. Both the tackler and ball carrier were found to be at greater risk for high magnitude head impacts when exhibiting poor form as defined by specific tackling recommendation criteria.

These data suggest that individualized interventions encouraging proper form, especially for a subset of impact-prone players, may be beneficial in reducing high magnitude head impact exposure for an entire youth football team. This is especially critical because a majority of high-risk impacts are experienced in practice at the youth level. Results from this work could be applied by coaching staffs in youth football leagues to increase the safety of their athletes.

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INTRODUCTION

Approximately five million athletes play football every year in the United States,[7,9] and nearly 70% of these athletes are below the age of 14. This popular pastime is also associated with the highest incidence of concussion among team contact sports.[5,11] Additionally, recent studies have found increased risk for long-term neuropsychiatric consequences when players are exposed to contact football before age 12.[1] These consequences are tied to concussion history, but are even more strongly related to repetitive head impact exposure – regardless of whether acute injury is manifested.[15]

Previous studies have summarized overall head impact exposure in youth football teams.[6,7,9,10,25] Generally, youth players experience more impacts, and more high magnitude impacts, in practices than in games. Youth players experience approximately 240 head impacts per season, with around 10% of these being above 40 g.[3,7] The 95th percentile peak linear acceleration in youth players (43 ± 7 g) is lower than that seen in high school (56.4 ± 10.5 g) and collegiate players (62.7 g), but some accelerations among youth players can still reach magnitudes greater than 100 g.[7,8,11,23] Frequency and magnitude of head impact exposure generally scale with age and weight-based level of play in the youth age group.[12] More recent analyses have revealed that individual youth players' head impact exposure in games and practices are correlated.[22] Practice structure and coaching style have also been revealed as two causes of difference in head impact exposure among teams, both of which could be changed by league rules.[3,4] Some football organizations have changed their rules in recent years in order to limit contact in practice as a way of reducing head impact exposure for athletes.[16,21]

No studies to date have taken an in-depth look at individual player involvement in high-risk head impacts, nor have any studied how to modify individual-specific behavior to limit this

risk. Therefore, the first research objective of this thesis was to quantify individual player contribution to impacts involving head accelerations above 40 g. Individual player involvement was measured as any impact in which a given player or his teammate experienced a high magnitude acceleration during an impact, so as to capture a player's overall contribution to his team's high magnitude acceleration exposure. It was expected that the most skilled players and positions would have greatest involvement and present the best chance for reducing head impact exposure.

Other football organizations have aimed to reduce head impact exposure by modifying tackling technique. Tackling is a major part of football, and will likely always be a part of the game; as such, using proper tackling technique presents a major opportunity for reducing exposure. The prevailing technique taught to defensive players (tacklers) involves using the shoulder to make primary contact with the ball carrier while keeping the head away from contact.[20,24] A reduction in the number of concussions in practices was observed when teams implemented both modified tackling training and rules limiting contact during practice.[13]

No studies to date have investigated the association between tackling form and head acceleration outcome on an individual tackle basis. The second research objective of this thesis was to determine the influence tackling form had on head acceleration outcome in youth football players through the development and use of tackling form criteria. In addition, no currently available football technique recommendations are available for ball carriers. Therefore, this research objective included the development and use of criteria for ball carriers involved in a tackle, as well.

Finally, football helmets are commonly evaluated for certification and performance in a laboratory environment.[18,19] Lab tests can also be used to validate computer-aided design tools, which can enable design that is more efficient.[14,17] Material testing is typically carried out on a

tensile or compressive testing machine at deflection rates below 1 cm/s.[2] No methods currently exist to evaluate football helmets in a dynamic loading environment. This is necessary, as football helmets are commonly loaded by energy inputs far above the quasi-static range, and rate dependency in material properties likely exists.[19] The third research objective of this thesis was to develop and demonstrate a novel testing methodology for obtaining force-deflection curves of helmets under dynamic loading conditions.

CHAPTER 1

Are Specific Players More Likely to be Involved in High Magnitude Head Impacts in Youth Football?

Abstract

Youth football attracts approximately 3.5 million participants every year, but concern has recently risen about the long-term effects of experiencing repetitive head accelerations from a young age due to participation in football. The objective of this study was to quantify total involvement in high magnitude impacts among individual players in youth football practices. We explored the relationship between the total number of high magnitude accelerations in which players were involved (experienced either by themselves or by other players) during practices and the number of high magnitude accelerations players experienced.

A local cohort of 94 youth football players (mean age 11.9 ± 1.5, mean body mass 50.3 ± 16.4 kg) from four different teams were recruited and outfitted with helmet-mounted accelerometer arrays. The teams were followed for one season each for a total of 128 sessions (practices, games, and scrimmages). Players involved in all high magnitude (greater than 40g) head accelerations were identified through analysis of practice film.

Players who experienced more high magnitude accelerations were more likely to be involved in impacts associated with high magnitude accelerations in other players. A small subset of six players (6%) were collectively involved in 230 (53%) high magnitude impacts during practice, were involved but did not experience a high magnitude acceleration 78 times (21% of the 370 one-sided high magnitude impacts), and experienced 152 (30%) of the 502 high magnitude accelerations measured. Backs were involved in the greatest number of high magnitude impacts in practice and experienced the greatest number of high magnitude accelerations. Team was an important factor, as one team showed much greater head impact exposure than all others.

This study shows that targeting the most impact-prone players for individualized interventions could reduce high magnitude acceleration exposure for entire teams. These data will help to further quantify elevated head acceleration exposure and enable data-driven interventions that modify exposure for individual players and entire teams.

Introduction

Football is among the most popular sports in the United States at all ages, with over 70% of its participants being at the youth level.[13,20,29] This team sport is also associated with the highest incidence of concussion among participants.[22,30] Recent research has suggested that sports-related concussive and sub-concussive impacts, even at the youth level, may be linked to neurodegeneration later in life.[2,31,33] As a result, a number of organizations have moved to change the game to prevent not just injury, but exposure to head impacts, as well. Current approaches include changing rules to eliminate high-velocity drills and plays, changing technique through tackling programs, and creating better equipment.[3] Reducing head impact exposure through interventions has become a topic of discussion in the scientific literature and among youth football leagues.[3,18,22,27,28,30,35,38] Examples of these interventions include limiting contact drills in practice, especially those exposing players to head impacts not representative of game situations,[11,13,34,41] and attempting to improve tackling technique by teaching players to keep their head away from contact during a tackle.[44]

Studies quantifying exposure to high magnitude acceleration in American football have revealed exposure varies in magnitude and frequency between individual players due to differences in position, amount of playtime, and athleticism. [9,10,17,19,32,40] Level of play and past experience in football are also important, and these factors may have larger influence at the youth

level.[1, 2, 22-25] Among youth football players, age- and weight-based level of play substantially influences the number of high risk head impacts experienced.[26] Tolerance to these head impacts also likely varies by individual due to differences in age, gender, past exposure to head injury, size, and a range of other factors.[1,4,6-8,12-15,20,23-25,37,45]

Aggregate analyses have been used to characterize head acceleration exposure in youth football players.[12,13,20,21,42,45] A study of 50 youth players ages 9-12 showed a large range of player exposure at this level of play.[13] Player-to-player variance in impact frequency and magnitude among 7-8 year old players has been attributed to player experience.[45] Frequency and magnitude of head accelerations in games scales with frequency and magnitude of head accelerations in practices in individual youth players.[42] While these studies provide a summary of exposure in youth players, there has yet to be an in-depth study quantifying individual-specific involvement in head accelerations at the youth level.

The objective of this study was to quantify total involvement in high magnitude impacts among individual players in youth football practices. We explored the relationship between the total number of high magnitude accelerations in which players were involved (experienced either by themselves or by other players) during practices and the number of high magnitude accelerations players experienced among four youth football teams and three position groups. These data will help to further quantify elevated head acceleration exposure and enable data-driven interventions that modify exposure for individual players and entire teams.

Methods

Head impact data from 94 male youth football participants (age 11.9 ± 1.5, body mass 50.3 ± 16.4 kg) from three recreational league teams and one middle school team were collected over

the course of two seasons for a total of four team-seasons (Table 1.1). Ages ranged from 9 to 14 across all teams. Participants were recruited to be a part of this study by obtaining written consent from parents of each youth athlete and verbal consent from each athlete. This study was approved by the Virginia Tech Institutional Review Board and all standard procedures were followed in regards to the research of human subjects and minors.

Table 1.1: Summary of Team Demographics

Team	Level of Play	Age Range (years)	Age (years)	Body Mass (kg)	Experience (years)	Players
			Avg. ± SD	Avg. ± SD	Avg. ± SD	
A	Junior Rec.	9-11	9.9 ± 0.6	38.9 ± 9.9	1.85 ± 1.46	27
B	Senior Rec.	11-13	12.4 ± 0.7	47.1 ± 13.4	3.40 ± 2.48	20
C	Senior Rec.	11-13	11.9 ± 0.6	51.4 ± 11.8	2.82 ± 2.19	18
D	Middle School	12-14	13.5 ± 0.6	62.8 ± 16.8	4.11 ± 2.72	29
Total		9-14	11.9 ± 1.5	50.3 ± 16.4	3.04 ± 2.39	94

Before the season, demographic information was collected from each player including their age, body mass, and experience playing contact sports. Experience playing contact sports was given by parents in the form of sport and number of years played. Restrictions were not placed on the type of sport the parents could report as contact, and responses varied (e.g. martial arts, wrestling, basketball).

Helmets of subjects were instrumented with the Head Impact Telemetry (HIT) system (Simbex, Lebanon, NH; Sideline Response System, Riddell Inc., Chicago, IL). This system

consists of a six-accelerometer array inserted into either a Riddell Revolution or a Speed model helmet and communicates with a sideline computer during all games and practices. Data were collected at 94 practices (26 Team A, 15 Team B, 31 Team C, and 22 Team D), 31 games (8 Team A, 8 Team B, 7 Team C, and 8 Team D), and 3 scrimmages (Team D). Resultant linear and rotational head acceleration values were measured for each impact event players experienced.16,17,36,39 Data collection was triggered when any one of the six channels exceeded 9.6 g of linear acceleration, and a threshold of 10 g resultant linear acceleration was used to discriminate between impact and non-impact events.5,6

For the purposes of this study, a high magnitude acceleration (HMA) was defined as any resultant linear acceleration greater than or equal to 40 g. A high magnitude impact (HMI) was defined as any collision in which two players were involved and at least one experienced an acceleration greater than 40 g. High magnitude accelerations account for approximately the top 10% of all accelerations experienced by youth football players.10

Video recordings using Sony HDR-CX160 and HDR-CX440 camcorders (Sony, Tokyo, Japan) and activity logs of each session were used to verify all high magnitude events. All players involved in each high magnitude impact during practice sessions were also identified from film and logged. Both players were identified for all except 30 high magnitude impacts (< 6% of all high magnitude practice impacts recorded) due to uncertainty associated with group tackles or poor video quality of the event (e.g. low-light conditions). Total player involvement in high magnitude impacts was identified for practices only, as this was the only session type for which acceleration data were available for both players involved in a given impact.

Players were grouped into general position categories based on playtime at each position during games and the playing style of those positions. At the youth level, players typically play

one offensive and one defensive position of similar playing style. Three position groups were used to account for playing both ways in competition: Backs (n = 30 - quarterbacks, running backs, linebackers), Line (n = 36 - offensive/defensive line, tight end), and Perimeter (n = 28 - wide receiver, safety, cornerbacks) (Table 1.2). All data are reported as median [25th – 75th percentile] unless otherwise noted.

Table 1.2: Position Group Summary by Team

Team	Backs	Line	Perimeter	Total
Team A	7	11	9	27
Team B	4	8	8	20
Team C	7	7	4	18
Team D	12	10	7	29
Total	30	36	28	94

High magnitude acceleration counts in practice sessions were compared using a linear model (factors: team, position, team by position). The linear model (R: lm) was analyzed for Type III SS differences (R: drop1) and a Tukey HSD post-hoc analysis (R: TukeyHSD) was performed when ANOVA results showed significant differences. Correlations were computed using Spearman rank-based correlation statistics (R: stat_cor). Results were deemed significant for $p < 0.05$. R was used for all statistical calculations (R Foundation for Statistical Computing, Vienna, Austria).

Results

A total of 13,909 accelerations were recorded for all players throughout the season: 8806 in practice and 5103 in games (Table 1.3). All teams recorded more head accelerations in practices than in games except Team B. In practices, there were 2552 accelerations (29%) experienced by players on Team A, 955 (11%) on Team B, 2980 (34%) on Team C, and 2319 (26%) on Team D. Using the predetermined threshold of 40 g linear acceleration, 502 high magnitude accelerations were recorded in practice as a result of 436 high magnitude impacts.

Table 1.3: Summary of Accelerations measured. HM = High magnitude. HMA = High magnitude acceleration (>40 g). HM Impact events were defined as interactions between two players in which at least one received a high magnitude acceleration. Multi-HMA Impact Events were defined as interactions between two players in which both received a high magnitude acceleration.

	All Accelerations (< 40 g and > 40 g)			HM Impact Events	Multi-HMA Impact Events	HMAs
	Practice	Game	Total	Practice only	Practice only	Practice only
Team A	2552	964	3516	98	12	110
Team B	955	1141	2096	49	8	57
Team C	2980	1093	4073	205	43	248
Team D	2319	1905	4224	84	3	87
Total	8806	5103	13909	436	66	502

High Magnitude Accelerations Experienced vs High Magnitude Impact Involvement

A positive correlation was found between the number of high magnitude head impacts in which a player was involved *without experiencing a high magnitude acceleration* and the number of high magnitude accelerations a player experienced in practices over the course of a season (Figure 1.1).

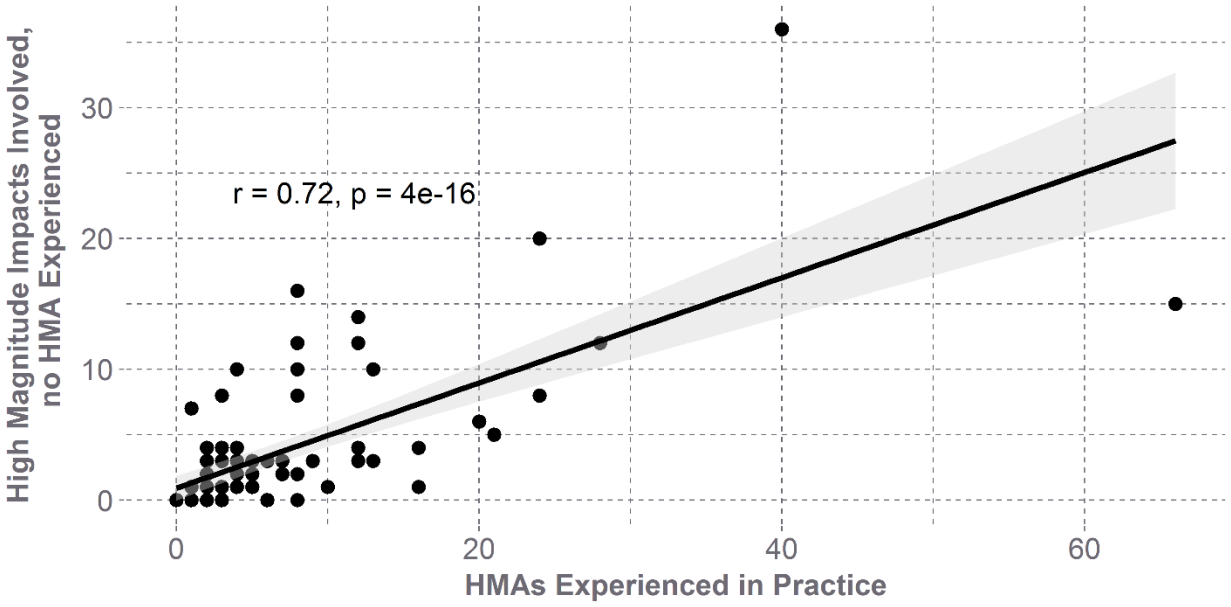

Figure 1.1: Players who experienced more high magnitude accelerations themselves were more likely to be involved in impacts associated with high magnitude accelerations in other players. Spearman rank-based methods were used to calculate correlations. Players involved in HMIs could have been the striking (causing) or struck player. *Symbols* represent individual players, *line* represents the Spearman correlation, and *shaded area* represents 95% CI for correlation.

Team A players experienced 3.0 [1.0 – 5.0] high magnitude accelerations in practices over the course of the season. Team B players experienced 2.85 [0.0 – 4.25], while those on Team C

experienced 13.8 [3.25 – 21.75] high magnitude accelerations. Players on Team D recorded 2.0 [1.0 – 3.0] high magnitude accelerations per player in practices (Figure 1.2). A small handful of players were involved in a majority of high magnitude impacts in practices on all four teams. Six players were identified as outliers in both number of impacts in which they were involved during practices and number of high magnitude accelerations experienced. These six players (6%) (two lineman from Team A; two backs from Team C; and two backs from Team D) were collectively involved in 230 (53%) of all high magnitude impacts during practice, were involved but did not experience an HMA 78 times (21% of the 370 one-sided HMIs), and experienced 152 (30%) of the 502 high magnitude accelerations measured.

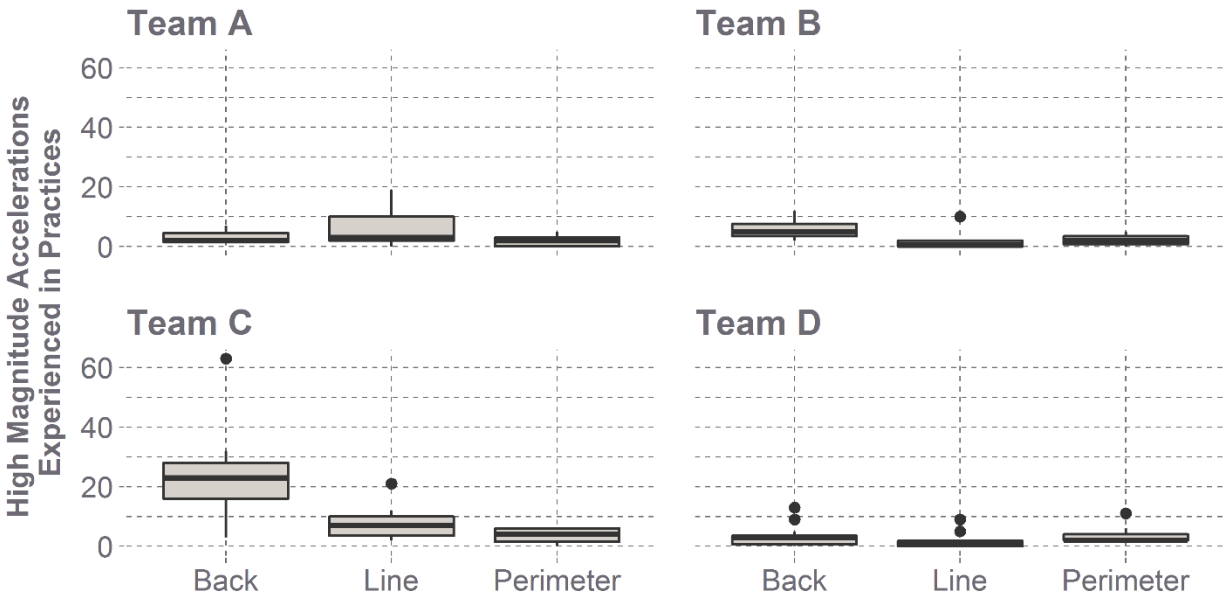

Figure 1.2: Distributions of high magnitude accelerations received in practices over an entire season by team and position group. The *thick black lines* within each box represents the median, the *boxes* represent the interquartile range (IQR) defined as 25^{th}-75^{th} quartiles, and the *whiskers* represent the fences (1.5 * IQR). Any data point (*dots*) outside the fences represent outliers.

The overall proportion of high magnitude impacts in which a player experienced a high magnitude acceleration was quantified by team and position (Figure 1.3). A Tukey Post hoc test showed that Team C players were involved in more high magnitude impacts in practice than any other team ($p \leq 7.76e\text{-}5$). Other teams were similar in their number of impacts. Comparable results were produced for the number of high magnitude accelerations experienced, with Team C accounting for the most (49%).

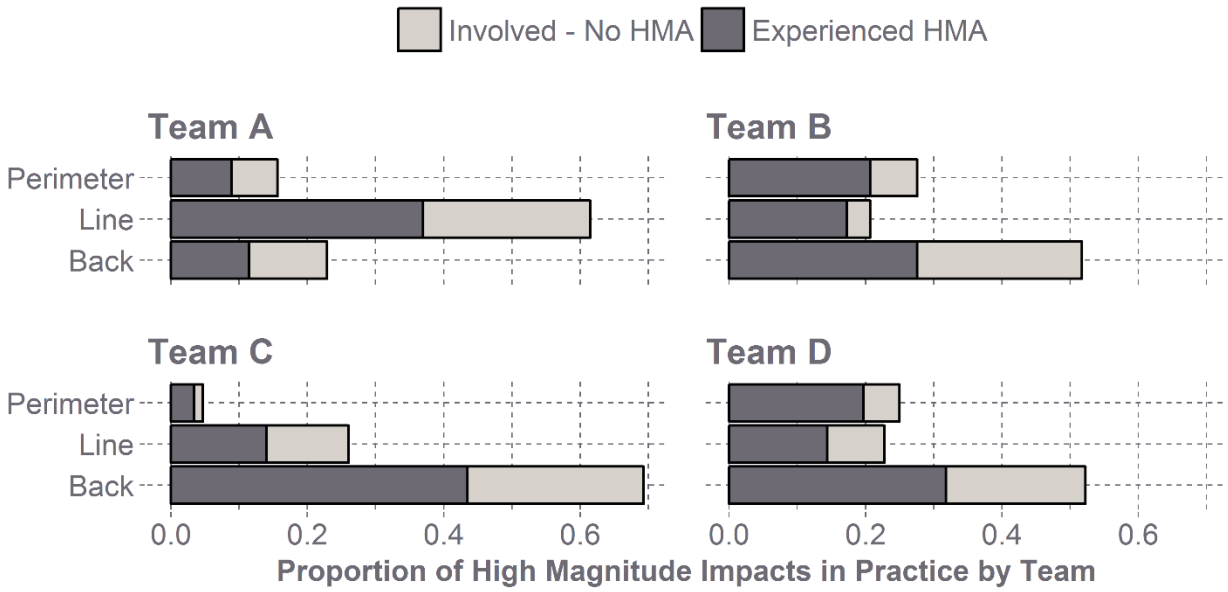

Figure 1.3: Bar graphs showing proportion of team's high magnitude practice impacts in which players experienced a high magnitude acceleration by position.

Additionally, Backs were involved in more high magnitude impacts than Perimeter players ($p = 2.6e\text{-}3$) and showed evidence of greater involvement than Linemen ($p = 0.058$). Perimeter and Line players did not differ in the number of impacts in which they were involved. Similar results were found for number of high magnitude accelerations purely experienced, with Backs having more than Perimeter and Line players (Figure 1.4). Adding an interaction term between

team and position showed that Backs on Team C team had greater propensity for impacts and high magnitude accelerations than any other position group on any team in the study.

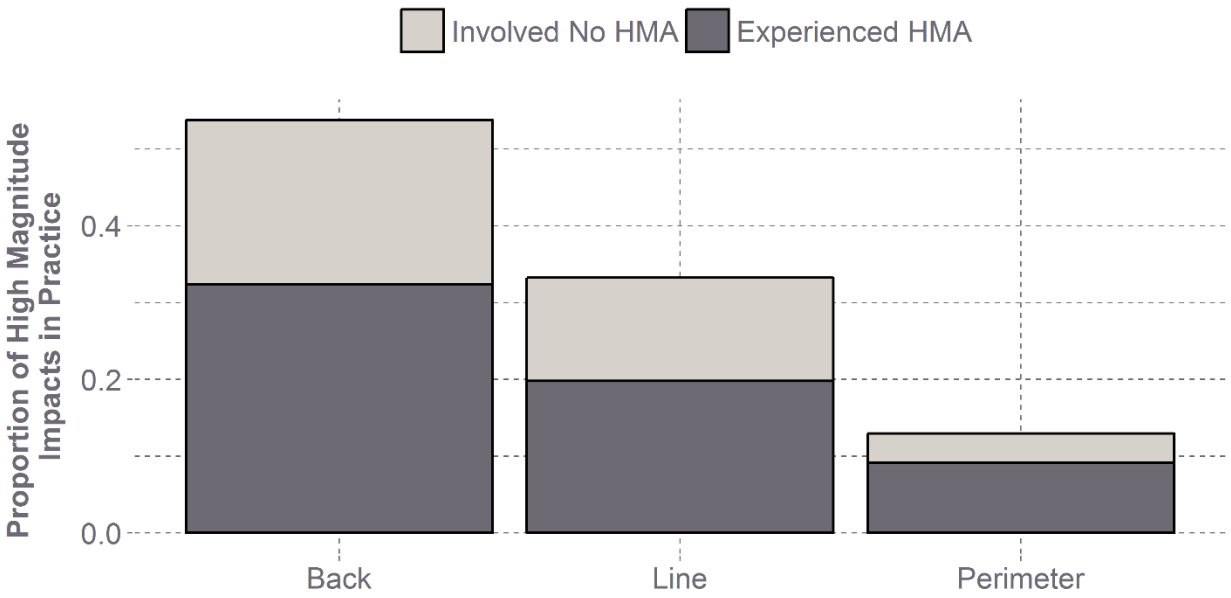

Figure 1.4: Bar graph showing proportion of position's high magnitude practice impacts in which players experienced a high magnitude acceleration across all teams.

Discussion

Previous studies have presented individual-specific head acceleration data, which revealed the existence of players on youth football teams who experience greater head impact exposure than their peers.[12,13,20,21,45] Experiencing a greater number of head impacts in practice than in games is common at the youth level, which is consistent with this analysis.[11,13,20] Head impact exposure varied within this cohort of 94 youth football players. This variance can be partially explained by team and position, as Team C players were exposed to more impacts than others were, and Backs generally experienced a greater number of high magnitude impacts than did the other position groups. However, even within the Backs position group, head impact exposure varied greatly.

A small subset of players were involved in a majority of the high magnitude head accelerations recorded. These players were unarguably among the most athletic and competitive players on their team and therefore received the most playing time, ball carrying time, and were involved with the most drills during practice and plays during games. Additionally, these players would likely have been paired against other teams' most athletic players during games, increasing their chances of high magnitude collisions outside of practice (Figure 1.5). It is notable that some players played for different teams across both years of this study and had different roles on each respective team. Impact-prone players on one team were not necessarily the most impact-prone the next year, and this is likely caused in part by their role on a given team (e.g. position, playtime). Thus not only do certain individuals inherently exhibit greater involvement in high magnitude impacts than their peers do, but their involvement is also influenced by their function on a team.

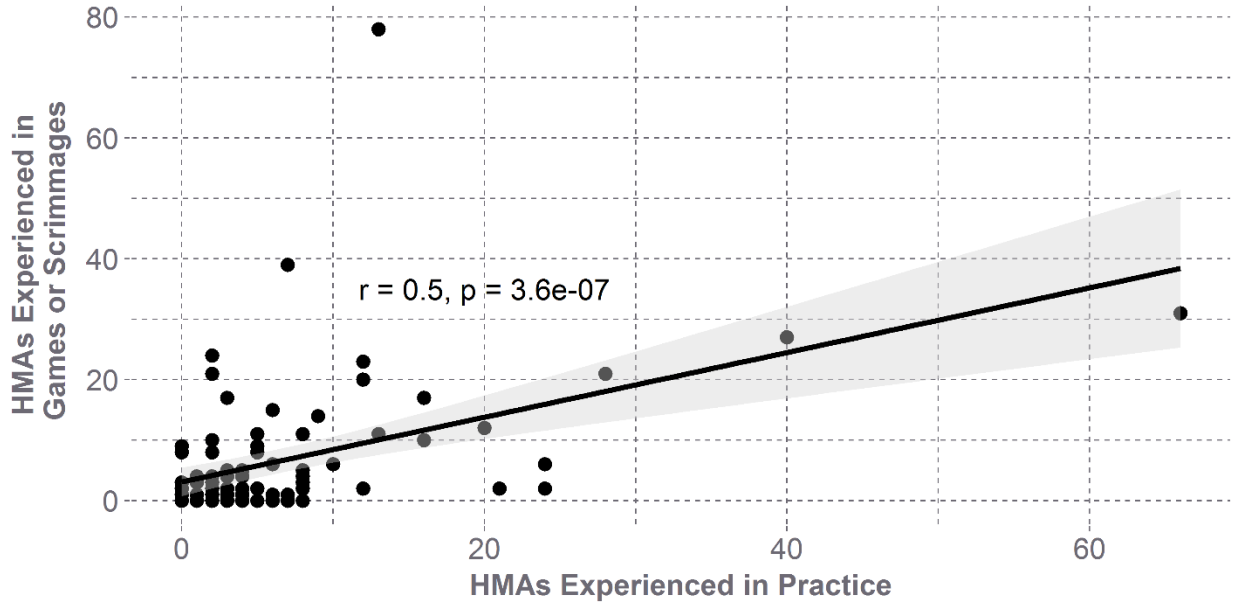

Figure 1.5: Number of high magnitude accelerations experienced in games was correlated with number of high magnitude accelerations experienced in practices. Spearman rank-based methods were used to calculate correlations. *Symbols* represent individual players, *line* represents the Spearman correlation, and *shaded area* represents 95% CI for correlation.

In this dataset, the players involved in more high magnitude impacts without experiencing head accelerations themselves also experienced more high magnitude head accelerations on average. This means there is likely a group of players responsible for a large number of the high magnitude impacts on any given team, putting others and themselves at higher risk for head injury. At the youth level, players are still learning proper tackling form and often deviate from the best tackling methods; leading with the helmet was observed in a number of impacts.

Player experience with contact sports, and football in particular, likely influences number of head impacts experienced due to increased confidence and skill.[45] Youth tackle football

generally cannot be played until athletes are nine years old; however, many individuals in this cohort had experience in contact sports beyond football. This increase in familiarity with contact could have increased their confidence relative to their peers and influenced their propensity for high magnitude impacts over the course of the season (Figure 1.6). Previous studies have found that coaching education strategies combined with guidelines for contact during practice is also most effective for older youth players, specifically 11-15 year olds.[27] This may be because of the players' ability to accept such information, or could also be due in part to repeated coaching of proper technique over multiple years of play up until that point. Coaching style likely played a large role in head impact distribution across the teams in this study, as well. Coaching intensity has been shown to be a significant factor in high magnitude head impact exposure during practice, and specific drills can have higher impact rates than others.[10,11]

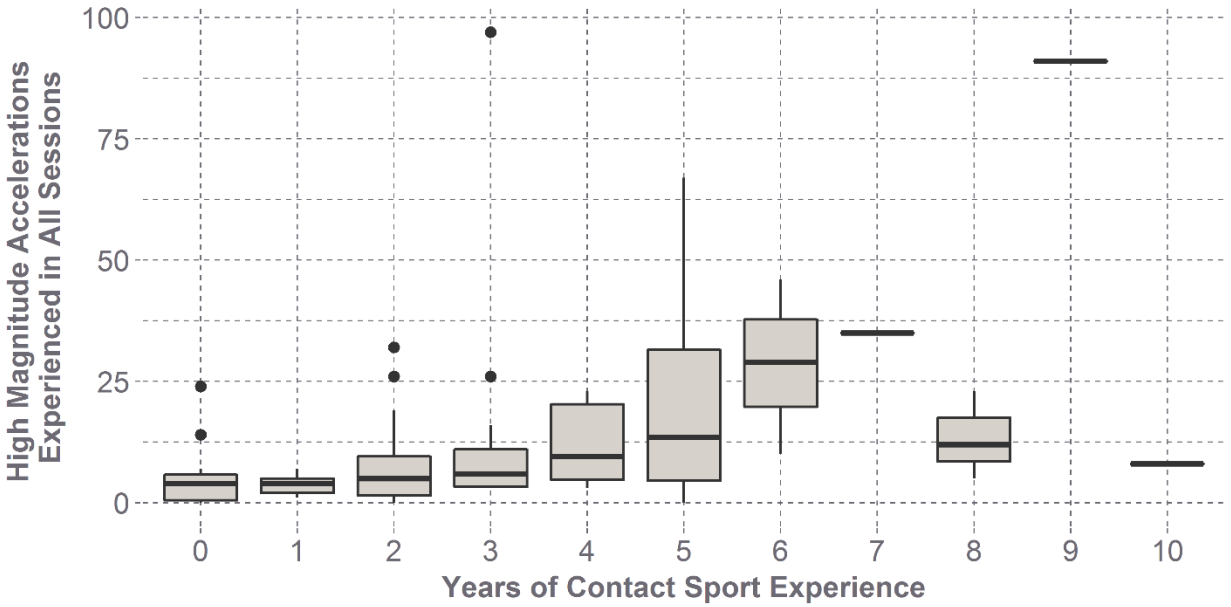

Figure 1.6: A generally increasing trend was observed between years of experience playing contact sports and high magnitude accelerations experienced in practice across all teams. The *thick black lines* within each box represents the median, the *boxes* represent the interquartile range (IQR) defined as 25th-75th quartiles, and the *whiskers* represent the fences (1.5 * IQR). Any data point (*dots*) outside the fences represent outliers.

These data suggest that if players who account for a majority of high magnitude impacts could be taught to tackle in a way that reduces the likelihood of high magnitude acceleration for themselves and others, their entire team would benefit. This is especially true because a majority of high magnitude impacts occur during practice at the youth level.[10,11,20,45] Those players who are not causing a majority of high magnitude impacts should still be taught proper technique, as they could still be exposed to high magnitude impacts during practice (via their teammates) and in games. They will also experience a greater frequency of high magnitude impacts if they continue to play at higher levels.[9,43] However, to maximize effect, tackling training that targets the few

impact-prone individuals on a team could drastically minimize exposure in practices for all players.

Limitations of this study include the error associated with the HIT system – subject to up to 15.7% error for a given individual impact, but less than 1% error on average.[5,11] Additionally, this study used a small sample of players from four youth football teams across two seasons. Future studies should incorporate a larger sample with a wider demographic range in order to scale the conclusions to the overall population of youth football players.

Conclusions

This study highlights the potential need for individual-specific intervention to reduce high magnitude acceleration exposure for youth football teams. Individual players who were involved in a majority of high magnitude impacts without experiencing a high magnitude acceleration themselves also experienced the majority of high magnitude accelerations over the course of the season. A small subset of individual players were involved in a majority of high magnitude impacts in practices and thus present the greatest opportunity for reducing exposure for an entire team. High magnitude acceleration exposure generally increased with player experience. Team and position within team were the best predictors of exposure, as Team C showed noticeably higher exposure. Backs, who were involved in a majority of ball carrying, were also involved in a majority of high magnitude collisions on every team but one. This study sets the framework for identifying players with elevated head impact exposure in youth football leagues and underlines the necessity for a multi-pronged approach to reducing head acceleration exposure in youth football players.

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CHAPTER 2

Association between Tackling Technique and Head Acceleration Magnitude in Youth Football Players

Abstract

In order to address concerns about head injury in youth sports, a number of youth football organizations have developed rules and recommendations surrounding the tackling form that should be used in order to reduce unnecessary head impact exposure. Reduction in injury has been suggested with these programs, but association between tackling form and head acceleration magnitude has not been studied previously. To address this knowledge gap, grading criteria were developed from multiple youth organizations' recommendations for a collision. A total of 142 tackles from a youth football team were graded. Head acceleration data were collected from helmet-mounted accelerometer arrays. An association was found between poor form and resultant head acceleration being greater than 40 g for both the tackler and the ball carrier. This study demonstrates the potential usefulness of tackling technique coaching programs in youth football.

Introduction

Concussions continue to be a major health concern in American football. With a large majority of players of this contact sport at the youth level, the accumulation of head impact exposure over a lifetime has begun to be extensively studied as a potential risk factor for impairment later in life.[1,4,6,8,16] Specifically, Alosco et al.[1] found that exposure to football before age 12 resulted in a twofold increase in odds of having clinically impaired scores on self-reported measures of executive function and behavioral regulation, depression, and apathy in former amateur and professional football players. Montenigro et al.[8] suggested that this increase in odds may be more strongly related to repetitive head impact exposure than other metrics, including

concussion history. Associations such as these have led a number of organizations to seek methods of reducing head impact exposure in athletes, rather than only addressing injuries. The three best strategies today are thought to be development of better equipment, rule changes prohibiting head contact, and teaching better technique when contact occurs.[2,5]

Recently, multiple organizations have created or prioritized rules which prohibit certain tackling techniques, and some have even started programs teaching what the organization considers to be proper tackling technique.[9-11,14] Previous studies have shown these types of programs have resulted in less injury overall. Kerr et al.[7] found that injury rates for all types of injuries in games were lower among teams implementing USA Football's Heads Up Football program. Concussions were only found to be reduced in practice if the Heads Up Football program was implemented and Pop Warner's practice rules were also followed, which limited time allowed for contact in practices and eliminated high-speed, head-on tackling drills. These findings scaled with age, with stronger effects from these tackling recommendations and rule changes seen in players aged 11-15 rather than those 5-10 years old. There has been disagreement as to the degree of effectiveness these programs truly have, as reported concussion reduction may have been skewed when initially reported.[7,12] To date, tackling technique programs have only been studied in terms of concussion incidence numbers, but none have attempted to determine if individual impacts with proper technique actually result in lower head accelerations for the athletes involved.

The objectives of this study were to discriminate between good and poor impact form for both a tackler and ball carrier in distinct impacts occurring in youth football practices via a generalized grading scale and to determine if poor technique was associated with increased head acceleration magnitude.

Methods

Head impact data were collected from 18 youth football players (age 11.9 ± 0.6 years, weight 51.4 ± 11.8 kg) on a local youth recreation league team. Players had not been formally trained on any tackling technique outside of conventional coaching. Linear acceleration data were collected using previously validated helmet mounted accelerometer arrays which incorporate six single-axis linear accelerometers (Head Impact Telemetry System, Simbex, Lebanon, NH).[3] The devices use an algorithm which calculates linear acceleration using the signals from all six accelerometers. The pre-set trigger for the device to record and download an impact was 10 g. Any impacts below this threshold were not recorded. This study was approved by the Virginia Tech Institutional Review Board (IRB # 15-517) on May 5, 2017 in order to involve human subjects. Standard procedures were followed using de-identified subject ID numbers, requiring parental and coach consent as well as minor subject assent; all wording was screened and cleared for coersive consent language.

A tackling technique grading scale was developed using criteria from a variety of modern youth football tackling programs that recommend keeping the head out of the impact (Table 2.1). These modern criteria are at odds with some previous criteria in that previous criteria recommended contacting the ball carrier with the helmet.[13] New criteria were selected based on their priority given to avoiding head impacts. Some information from USA Hockey's checking guidelines were also used, as these guidelines include useful recommendations about absorbing an impact, whereas most tackling programs only address criteria for a tackler.[15]

Table 2.1: Grading criteria used to evaluate individual impacts for the tackler and ball carrier in a one-on-one impact. Players performing any of the failing criteria listed in the given phase were given a fail for that phase. Phases were defined as approach – advancement toward opposing player up until moment of contact; impact – moment when two players collide; and drive – period following contact until drill is over, as signified by a coach's signal.

	Approach	**Impact**	**Drive**
Tackler	Feet spread less than shoulder width	Does not lead with near shoulder	Does not wrap with both hands
	Only lowers torso, bends at hip rather than knees	Does not initiate contact, shies away	Stops attempting to move legs
	Face directed downward, head not up	Aims shoulder too high (head) or too low (knees) into ball carrier	
		Does not keep head up	
Ball Carrier	Feet spread less than shoulder width	Does not lead with near shoulder	Stops attempting forward progress
	Only lowers torso, bends at hip rather than knees	Does not initiate contact, shies away	
	Face directed downward, head not up	Does not tuck ball and elbow	
		Does not keep head up	

These grading criteria were used to evaluate 142 impacts from video of one-on-one tackles from a variety of drill types in practices at different points throughout the season. Three distinct phases of a tackle were identified and graded individually: approach, impact, and drive. If a player failed to meet any of the criteria for a given phase, a fail (0) was given. If all criteria were met for a given phase, a pass (1) was awarded. Total scores across the three phases were used to dichotomize tackles into good (summed score ≥ 2) and poor (summed score ≤ 1). All impacts

were evaluated by a single grader to determine if significant association existed between tackling grade and head acceleration. The grader was familiar with tackling form evaluation and all players and coaches in this study.

Based on previous analyses, a threshold of 40 g was used to classify high magnitude impacts for this population.[5] This threshold resulted in high magnitude impacts accounting for approximately the top ten percent of data collected over the course of the season. A chi-square test for independence was used to determine the association of tackling form (good/poor) with presence of high magnitude acceleration (Y/N). Results were deemed significant for $p \leq 0.05$, and all statistical calculations were completed in R (R Foundation for Statistical Computing, Vienna, Austria).

Results

A total of 142 tackles were graded; three cases could not be graded because they involved players not enrolled in the study. This resulted in 281 total grades, one for the tackler and the ball carrier involved in each tackle. Of the graded impacts, 92 interactions resulted in high magnitude accelerations and 189 resulted in low magnitude accelerations. Tacklers saw 48 of the 92 high magnitude accelerations, while the ball carriers received the other 44. A total of 146 tackles passed overall, 61 for the tacklers and 85 for the ball carriers. Acceleration distributions by grade show a generally decreasing trend with increasing grade (Figure 2.1).

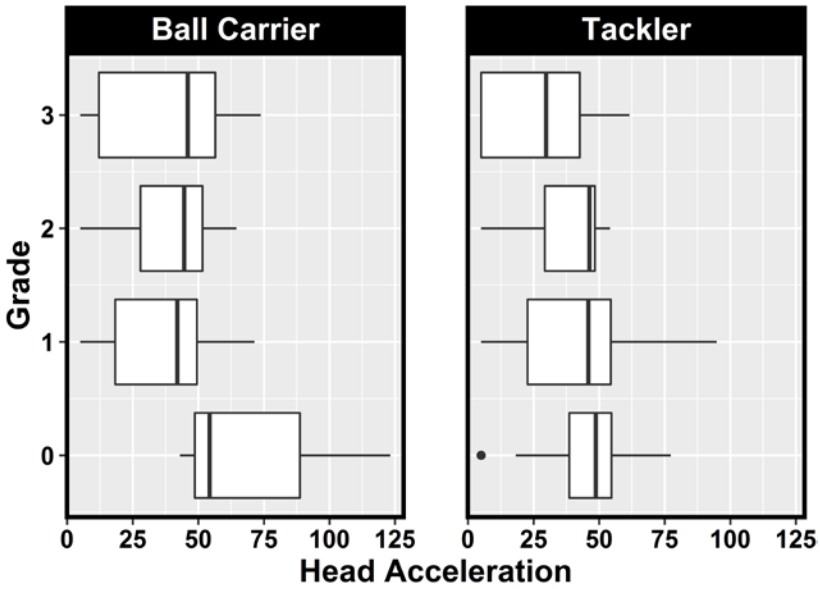

Figure 2.1: Head acceleration magnitude showed a generally decreasing trend with overall tackling grade for both positions in this drill. Tackles receiving a summed grade of 2 or greater were considered good form, while tackles receiving 1 or less were considered poor form. All tackles in which a linear acceleration was not recorded were assumed to have not reached the system's trigger threshold of 10 g. These tackles were presumed to be between 0 and 10 g, and were therefore coded as the average of 5 g.

When combining all grades from tacklers and ball carriers, significant association between high magnitude accelerations and poor overall grade was identified ($p = 0.009$). By position, tackles showed significant association between high magnitude accelerations and poor overall grade for the tackler ($p = 0.005$), but not for the ball carrier ($p = 0.542$). By phase, approach and impact for the tackler were associated ($p = 0.013$ and $p = 0.001$, respectively), and the impact phase for the ball carrier displayed good evidence of association with head acceleration ($p = 0.072$). No other phases showed association between high magnitude accelerations and poor impact grade (Figure 2.2).

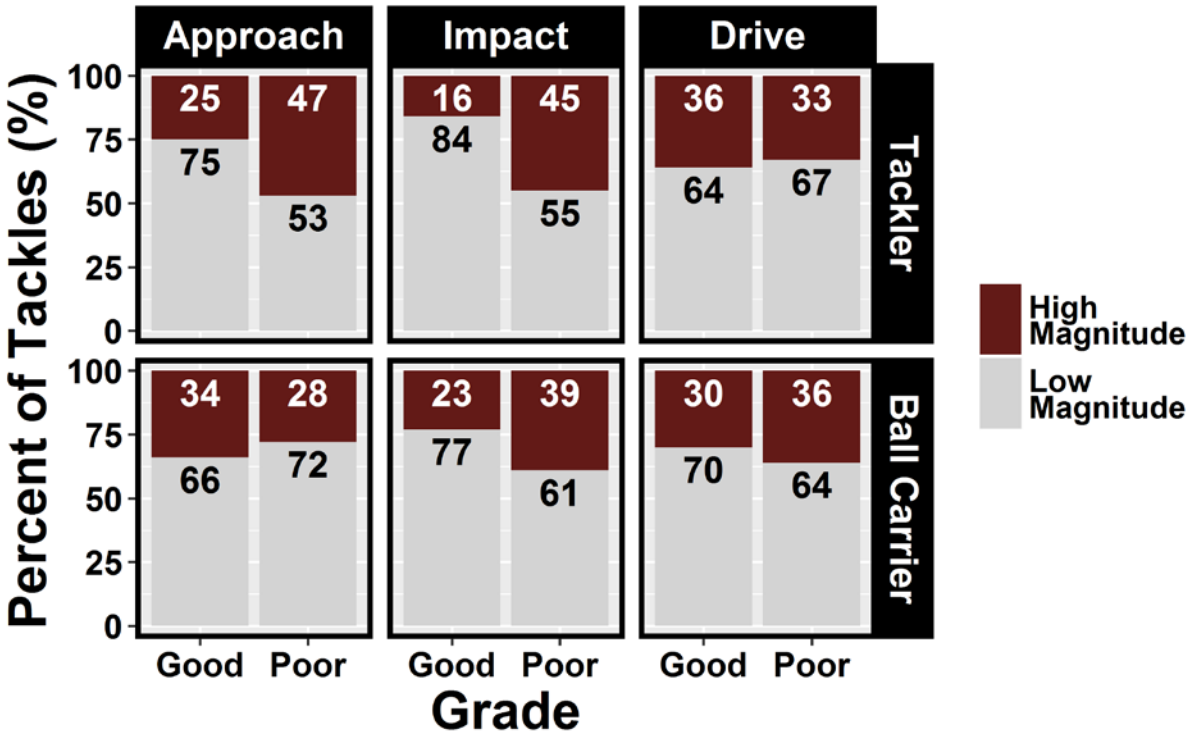

Figure 2.2: Grade was shown to be associated with high magnitude accelerations in the Approach (p=0.013) and Impact (p = 0.001) phases for the tackler, and to display good evidence of association with outcome in the Impact phase (p = 0.072) for the ball carrier.

Video quality varied by practice and drill type. Some phases of certain tackles were difficult to grade due to decreased video quality. Examples of good and poor grades for each phase of both the tackler and ball carrier can be seen in Figure 2.3. The most significant phase for both positions was the middle impact phase, which resulted in 39-45% of poor tackles being high magnitude accelerations and over 77% of good tackles being low magnitude (less than 40 g).

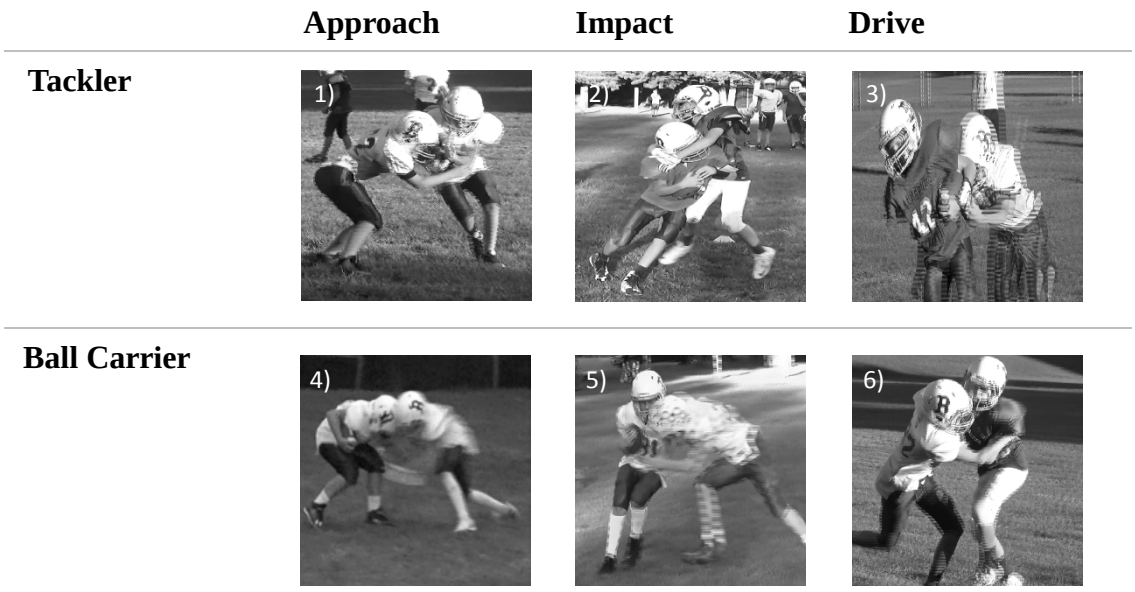

Figure 2.3: Exemplary failing tackles for the tackler and ball carrier. First row from left: 1) the tackler puts his head down and in the path of the ball carrier; 2) the tackler leads with his chest and aims too high; 3) the tackler does not wrap the ball carrier. Second row from left: 4) the ball carrier directs his face downward, 5) the ball carrier does not initiate contact, and 6) the ball carrier (right) stops attempting forward progress after collision.

Discussion

Although participants had not been trained on the tackling criteria used to evaluate their tackling form in this study, these players exhibited both good and poor form as defined by the established criteria during their practices. Tackling form did have an association with acceleration magnitude outcome, especially for the tackler, in this group of youth football players during one-on-one tackles. For both position groups, the impact phase was the most significant phase of the collision in determining acceleration level outcome. The drive phase was seen to have the least significant association for both positions.

The association between grade and outcome was thought to be high in the impact phase because this phase was graded at the moment of collision. Additionally, criteria for this phase

explicitly included using anything other than the near shoulder (e.g. the head) to lead when striking the opposing player. This suggests the impact phase should be stressed most during tackling technique training, as this is where the most improvement can occur to avoid high magnitude head impact exposure. Interestingly, a logistic general linear model relating approach grade to impact grade for both positions showed that the chances of obtaining a passing impact phase score were 2.4 times higher when the player first passed in the approach phase. This suggests that the approach is also a very important piece in avoiding high magnitude accelerations.

The drive phase did not appear to have a meaningful effect on the head acceleration magnitude in these impacts. This phase occurs after the impact has already taken place and does not have a large effect on the head's involvement in a tackle. Reanalyzing the data without the drive phase yielded very similar results: for overall scores, the tackler showed strong evidence for association between high acceleration and poor form, and the ball carrier showed similar trends but with less statistical evidence. As all the noted trends were similarly seen in both tackler and ball carrier results, it may be important to include sessions on absorbing a tackle in youth football programs in order to protect players on both sides of the ball.

Lower association among ball carriers with the tackle-absorbing criteria developed for this study suggest there may be other factors which were not addressed in this grading scheme that also influence acceleration outcome for these offensive players. This is likely due in part to the fact that ball carriers and tacklers have entirely different goals when entering a one-on-one collision scenario. The tackler is aimed only at bringing the ball carrier to the ground and impeding his progress. On the other hand, the ball carrier's goal is to get himself and the football past the tackler in any way he desires. This can include making a last-second cut to avoid the tackler, driving his body directly into the tackler, or any combination of these types of moves. In other words, a ball

carrier is less predictable and his criteria is therefore less generalizable. Regardless, criteria for training ball carriers might be relevant for youth football training programs, as ball carriers still received 48% of all high magnitude impacts graded in this study.

This study was limited by video quality, as some impacts occurred closer to the camera than others. In addition, grading in this study was completed by a single reviewer on a single team's tackling technique as a feasibility analysis and because of his familiarity with the subject population and tackling form requirements. The next step in this process will be to optimize the grading criteria to obtain sufficient inter-rater reliability with multiple reviewers.

Conclusions

Youth football players exhibit a number of different types of tackling form under conventional coaching. Youth sports organizations recommend shoulder tackling and keeping the head out of the tackle to avoid head injury and cumulative head impact exposure. This study reveals that these training techniques may have efficacy in that good tackling form did show significant difference from poor form in the acceleration magnitude outcome for this cohort of players. This study did not specifically investigate any one youth football organization's tackling recommendations; further research should be done to confirm that good form as defined by each organization is truly associated with better head acceleration outcome. In addition, these or similar grading criteria could be used to evaluate information retention and translation of learnings to the field among youth athletes trained in proper tackling technique.

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CHAPTER 3

Does Tackling Form Affect Head Acceleration in Youth Football Players?

Abstract

Youth football has become a topic of discussion in scientific literature because of the potential long-term neuropsychiatric effects of experiencing head impacts from a young age. To reduce head impact exposure, a number of organizations have begun teaching tackling techniques that emphasize using the shoulder and keeping the head out of tackles. Few of these training programs teach tackle absorption. In order to evaluate the effectiveness of using recommended tackling techniques, this study sought to develop and utilize a set of grading criteria for both tacklers and ball carriers and relate form during a tackle to head acceleration magnitude. Three teams consisting of 67 players (age 12.7 ± 0.95, age range 11-14, body mass 55.1 ± 16.2 kg) were instrumented with helmet-mounted accelerometer arrays and followed for one season each. No players were trained in specific tackling techniques outside of conventional coaching. Video of close-range tackling drills (with and without blockers) were used to develop a set of criteria for use with multiple raters. Two expert raters scored 105 impacts each. Six of the seven categories were found to have good interrater reliability metrics (TPA ≥ 79%, AC1 ≥ 0.65). Bending at both the knees and hips, leading with the shoulder or arm, and initiating contact rather than shying away were found to reduce risk of high magnitude (>40g) head impacts in tacklers. Keeping the eyes up or looking slightly to one side and avoiding dropping the head reduced risk in ball carriers. This study shows the potential effectiveness of training both tacklers and ball carriers in proper technique for collisions in youth football. This study does not endorse any specific tackling training program; each program's recommendations should be evaluated individually to determine its effectiveness in reducing head acceleration exposure.

Introduction

Over 5 million athletes play football every year in the United States, and approximately 70% of these players are under the age of 14, at the youth level. Recent information regarding potential long-term neuropsychiatric and cognitive consequences has raised concerns for football players, particularly those who are introduced to contact play before age twelve.[1,20] Factors pointing to the cause of these lasting effects include exposure to repetitive head contact, even without the manifestation of acute injury.[20,27] Reduction in head impact exposure through a number of methods have been suggested and can be grouped into three general categories: making equipment that better protects athletes, changing rules to limit exposure, and teaching the safest techniques for contact.[2,7,9,23,29] Contact will likely continue to be a part of the game of football, and as such tackling technique is extremely important in reducing head impact exposure.

A number of organizations have begun to implement strategies that are intended to reduce head impact exposure through proper technique training and limiting time allowed for contact during practice.[3,21-23,29] The National Federation of State High School Associations recommended in 2014 that member associations limit contact in practice to 60-90 minutes per week and 30 minutes per day during the season. Pop Warner youth leagues implemented rules beginning in 2012 limiting contact to one-third of practice time and prohibiting full speed head-on drills in which athletes begin more than three yards apart. USA Football and rugby tackling organizations teach tackling technique for defensive football players that involves keeping the head behind the ball carrier and out of the tackle. Previous studies have shown positive effect on injury prevalence when using USA Football's technique training in combination with Pop Warner's guidelines for contact restriction in practice.[18] These positive effects were found in practices only, which the authors contributed to USA Football's training program being targeted primarily at changing

practice technique. No technique program has been shown to reduce head impact exposure in games, where coaches have less control of the situations in which their players find themselves. Because youth players generally experience more head impacts in practice than competition and because a small group of players can account for a high proportion of high-risk accelerations experienced by youth players in practice, training individuals in proper form may help reduce head impact exposure for entire teams.[7,10,11,14,31]

There is no unilaterally accepted standard for how to tackle in football, and there is even less information on properly absorbing a tackle. Previous criteria have even suggested using the head to make a tackle.[28] No study to date has sought to determine if individual tackling technique influences head impact magnitude in youth athletes. The objective of this study was to enable reliable grading of both players involved in an impact using the most current criteria that suggests keeping the head out of a tackle. Afterward, we attempted to determine if poor form, as measured by these new grading criteria, was associated with greater head acceleration magnitude in youth football players.

Methods

This study consists of three main components: selection of criteria for grading impacts, measuring reliability of these criteria, and associating grades with head acceleration data.

Selection of Criteria

A number of governing organizations for youth sports involving contact have published information recommending specific technique for contact. For example, USA Football has advocated shoulder tackling for defensive players. Their technique involves breaking down the approach phase to put players in "hit position" and enable them to use their near or "leverage"

shoulder, keeping their head behind the ball carrier rather than across his or her chest.[29] Technique training has also become a part of the football market in the form of rugby-style tackling.[3] Few football organizations give recommendations for absorbing a tackle, though proper form is similar in both situations: the head should be out of the play. USA Hockey does give information on receiving a check, and their publications recommend tucking the arms and bracing for an impact.[30] Information from multiple organizations and sports were incorporated into these initial criteria for youth football tackling.

A single grader was used to determine feasibility of the initial criteria. These criteria included 3 phases – Approach, Impact, and Drive – for both the tackler and ball carrier. These phases each included several conditions, failing any of which was grounds for failing the entire phase. Impacts were evaluated by overall number of passing phases (0-3), and head acceleration was shown to be generally higher with lower score. The drive phase, occurring after initial contact is made, was shown to associate very little with head acceleration for both players involved and was not included in further analysis. These criteria were modified for use with multiple graders by breaking down the first two phases, Approach and Impact, into seven pass-fail categories.[15] Division of the phases allowed for more specific criteria to be defined and evaluated independently. Giving more options was also expected to produce better interrater agreement: dichotomization of multiple options into pass or fail bins allowed for small disagreements on what was visible in video analysis, while preserving overall agreement about tackling form. For example, it may be difficult to discern whether a tackler led with his arm or shoulder, but either option is still considered good form because the head is not the primary point of contact.

Seven categories for each player were selected for the multiple-rater grading criteria. These categories were, for the tackler, *1) Balance, 2) Posture, 3) Line of sight, 4) Leads with, 5)*

Shoulder use, 6) Initiation, and *7) Aims contact into*; and for the ball carrier, *1) Balance, 2) Posture, 3) Line of sight, 4) Leads with, 5) Shoulder use, 6) Initiation,* and *7) Ball Placement/Rib protection*. Several choices were given for each category, covering the range of possible movements commonly seen among youth football players making a tackle. For example, choices for the *Posture* category included (a) bending at both the hips and knees, (b) bending at the hips only, (c) bending at the knees only, (d) not bending at either joint, or (e) inconclusive (not discernable from video). Each choice represented either a pass or fail for that category. In the *Posture* category, only choice (a), bending at both the hips and knees, was considered a pass.

Measuring Reliability

Two expert raters, who were familiar with proper tackling form as well as the teams and coaching staff in the practice videos, were selected to grade an initial sample of 31 tackles (62 total grades each).[13,17] Each reviewer evaluated the impacts three times, with at least 24 hours elapsing between grading sessions. A selection made at least two of the three times was used as the final selection for each category.[24] The final selections for both raters were dichotomized into a pass (1) or fail (0) for each category, and these scores were compared using multiple inter-rater reliability measures. If a rater did not select the same choice at least twice, his choice was counted as a fail for that category.

Comparison of statistics for each category revealed some ambiguous wording and helped to define less useful categories. The "*Shoulder use"* category was eliminated from both the tackler and ball carrier criteria because it was reliant on the raters first agreeing in the "*Leads with"* category. This produced little new information for evaluating proper form. The "*Leads with"* category was renamed "*Primary contact made with"* to make the intent of the category more clear. Primary contact was defined as the part of the body taking the majority of the initial impact force,

even if that force shifts to another body part during the impact. Choices of "Arm" and "Shoulder pad" were both considered passing in the "*Primary contact made with"* category because of the difficulty of discerning a player's use of his arm as opposed to his shoulder pad in most videos. "Chest" was eliminated as a choice in the same category because this was seldom the primary point of contact used to lead and "Shoulder pad" accounted for this choice well. The final tackler category (*Aims contact into)* was reworded to be "*Primary contact into"* to similarly clarify intent. These changes as a whole helped to increase rater reliability across the criteria (Table 3.1).

Table 3.1: Final criteria selected for grading video impacts. Ball carriers and tacklers were graded separately, but shared criteria in five of the six categories. Bolded choices are those considered passing for that category. A single category could have multiple options resulting in receiving a "pass." Inconclusive was an additional option in all categories to account for times when graders could not see portions of an impact in video analysis. Definitions: Shy away – refers to the act of purposely stopping one's own momentum, without making a football cut move, in an attempt to soften an impact. Tucked into chest – ball carrier holding the ball within a region projected forward from his torso. *Ball carrier only.

Category	Pass	Fail
Balance	• Feet under shoulder • One foot in front of the other	• Feet closer than shoulder width
Posture	• Bends at both hips and knees	• Bends at hips • Bends at knees • Does not bend
Line of Sight	• Eyes looking to one side • Eyes looking toward ball carrier or straight ahead	• Eyes looking toward sky • Eyes looking toward ground
Primary Contact	• Initial force through shoulder pad • Initial force through arm	• Initial force through helmet • Initial force through knee/thigh
Initiation	• Initiates contact • Makes a football cut move*	• Shies away, hit comes to him
Primary Contact Into (Tackler)	• Ball carrier's body or shoulder	• Ball carrier's knees • Ball carrier's head
Rib Protection (Ball Carrier)	• Ball and arms tucked into chest	• Ball and arms out, not into chest.

There exist multiple schools of thought in regards to the effectiveness of Cohen's kappa at presenting the full picture of inter-rater reliability.[8,12,16] The most convincing arguments agree that authors should present more than a summary statistic to give the full picture.[8,25] For the sake of presenting all available information, we chose to present five statistics, which together represent the range of information regarding the reliability of the criteria: Cohen's kappa (K), total percent agreement (TPA), AC1, rate of positive agreement (P_{pos}), and rate of negative agreement (P_{neg}). Cohen's kappa was developed to correct for chance agreement between raters, under the assumption that if raters are not sure of the correct rating, they guess. Total percent agreement, though uncorrected for chance agreement, gives a summary of the amount of times raters agree overall. K is influenced by skew in rate of occurrence, which some believe is warranted.[8] However, AC1 was developed as a better summary metric for use when rates of occurrence are high or low.[16] This summary metric agrees well with K when rate of occurrence is equal across raters, but differs purposely otherwise. Finally, arguments for using K alongside other metrics have advocated the reporting of proportion of positive and negative agreements (P_{pos} and P_{neg}).[8] These statistics reveal the source of disagreement (if present) better than a single summary statistic by reporting the rate of agreement in positive (or negative) occurrence as a proportion of all raters' reporting of positive (negative) occurrence. Equations for all statistics are presented in Appendix A.

Acceptable values for each of these common metrics are also debated, because their values depend on multiple factors within each contingency table.[19,25] Baseline acceptable values of 80% TPA and 0.65 AC1 were chosen to represent good agreement in the presence of high or low rates of occurrence, because high and low rates of occurrence were observed in most categories.[17] Kappa, P_{pos} and P_{neg} were also reported for the sake of completeness.

Association with Head Acceleration

Importance of each category in the grading criteria was determined by comparison with the outcome measure of linear head acceleration. A total of 67 youth football players (age 12.7 ± 0.95, age range 11-14, body mass 55.1 ± 16.2 kg) on four teams were instrumented with helmet-mounted accelerometer arrays, which were worn in every session. Helmet-mounted accelerometers were part of the Head Impact Telemetry (HIT) system (Simbex, Lebanon, NH; Sideline Response System, Riddell Inc., Chicago, IL). This system uses a single-channel data collection trigger of 9.6 g and a resultant threshold of 10 g to discriminate between impact and non-impact events.[4,5] Video recordings of all practices were taken with Sony HDR-CX160 and HDR-CX440 camcorders (Sony, Tokyo, Japan). These videos served a dual purpose of providing video confirmation of all high magnitude impacts (>40g) and film of tackling drills used for developing and testing the grading criteria. Participants were recruited to be a part of this study by obtaining written consent from parents of each youth athlete and verbal consent from each athlete. The Virginia Tech Institutional Review Board approved this study and all standard procedures were followed in regards to the research of human subjects and minors.

The types of drills used for this study were all tackling drills involving two, four, or six players. Only the tackler and ball carrier were graded in each drill. If multiple players assisted on a tackle, this film was not used as a part of the dataset. Only head-on or side tackles were graded: no tackles in which the tackler had to approach from behind the ball carrier were used due to the fact the ball carrier would not be able to react in these situations. If multiple accelerations were measured during a single tackle, the highest linear acceleration value was used to represent the impact.

Two expert raters graded 105 impacts each, for a total of 210 grades each (105 for tacklers, 105 for ball carriers). Each category had one or two possible answers that were deemed "good form" and one or more answers deemed "poor form." These answers were used to dichotomize each response into a pass or fail for each category. Inter-rater reliability and association with acceleration outcome were calculated using these dichotomized responses. Each impact was paired with the accelerations of each athlete after grading was complete to avoid biasing the raters with knowledge of the outcome.

A chi-squared test for independence (R: *chisq.test)* was used to determine if passing or failing a category was associated with high magnitude acceleration, defined as greater than 40 g resultant linear acceleration.[6,7] Approximately 10% of the accelerations measured in the impacts in this dataset were high magnitude, which represents the amount typically found in youth football,[6] but makes drawing statistical conclusions more difficult. A Wilcoxon Rank Sum test (R: *wilcox.test*) was used as a supplement to determine a difference in the non-normal linear acceleration distributions for passing and failing grades in each category. Statistical significance was determined as $p \leq 0.05$. P-values are the result of bootstrapping contingency tables to 10000 iterations (R: *simulate.p.value)* in chi-squared results, unless otherwise noted. All statistical calculations were carried out in R (R Foundation for Statistical Computing, Vienna, Austria).

Results

Interrater reliability was acceptable in all categories except *Balance* (Table 3.2). All remaining categories with acceptable reliability had at least 79% TPA and an AC1 of at least 0.65.

Table 3.2: Summary of interrater reliability statistics for all seven categories included in final grading criteria for tackler and ball carrier form.

	Balance	*Posture*	*Line of Sight*	*Primary contact*	*Initiation*	*Primary Contact Into*	*Rib protection*
TPA	70%	79%	87%	80%	89%	83%	87%
AC1	0.494	0.667	0.761	0.653	0.852	0.690	0.847
K	0.264	0.437	0.691	0.539	0.496	0.605	0.000
P_{pos}	0.790	0.861	0.901	0.856	0.934	0.871	0.928
P_{neg}	0.474	0.559	0.789	0.672	0.556	0.727	0.000

Overall, summed scores showed a general trend of decreasing with increasing head acceleration magnitude across both raters (Figure 3.1). This is especially true if only the score bins with 20 or more impacts are considered (10% of all grades for each rater). Bins for scores of 3 or greater had more than 20 impacts in them. The highest scores showed the lowest linear accelerations distribution across both raters. Each category exhibited different interrater reliability and different association with high magnitude head acceleration.

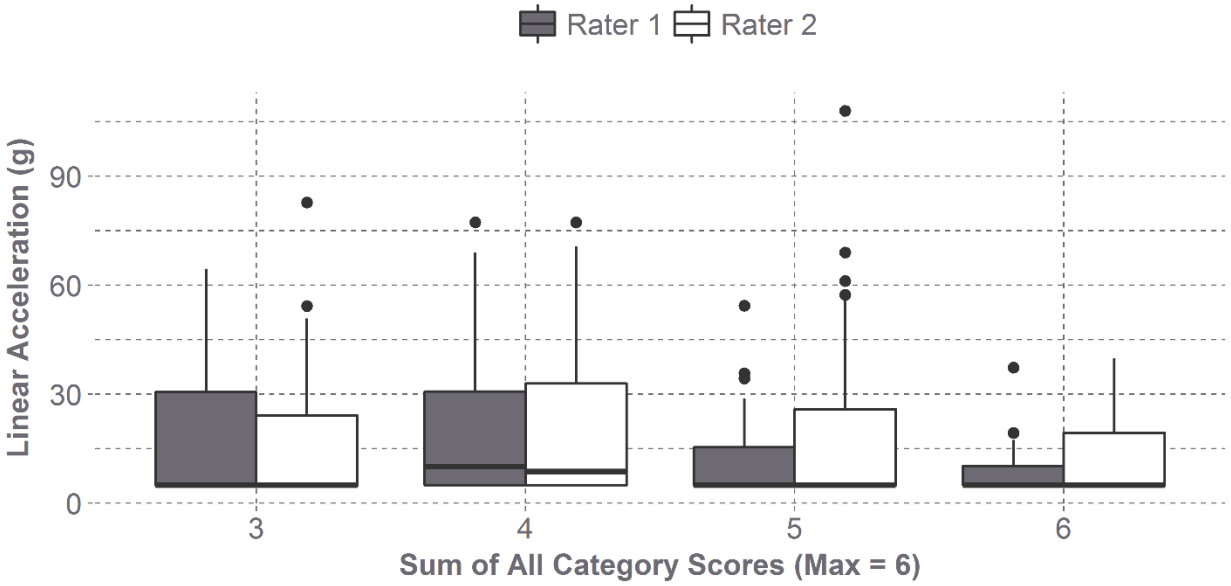

Figure 3.1: Boxplots showing sum of all category scores for both tacklers and ball carriers combined. Higher scores, corresponding to better tackling form, showed the lowest accelerations in bins with at least 20 ratings (all except Score = 1 and 2). Rater 1's scores are on the left in each x-axis bin, and Rater 2's scores on the right.

Balance

The *Balance* category exhibited the least interrater reliability, with 70% TPA and AC1 = 0.494. This category did not meet the minimum thresholds of at least 80% TPA and AC1 = 0.65 and was therefore deemed too difficult to grade using video analysis. This category also showed little ability to discriminate between high magnitude and low magnitude accelerations for either rater in both position groups ($p \geq 0.728$) (Figure 3.2). In addition, over linear acceleration distributions showed no difference between passing and failing grades ($p \geq 0.417$).

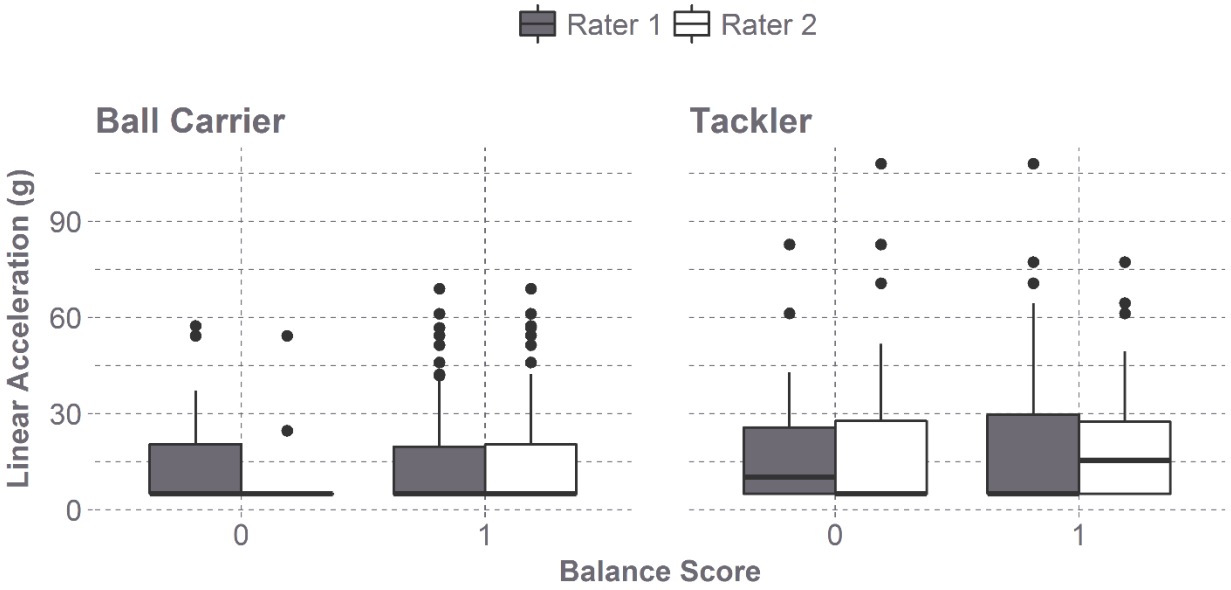

Figure 3.2: Boxplot showing Balance score for both positions in tackling drills. This category showed little overall association with high magnitude impacts and could not be graded reliably from practice video. Distributions did not differ for either rater. 1 = Pass, 0 = Fail.

Posture

The *Posture* category showed reasonably good interrater reliability with TPA (79%) and AC1 = 0.667. These scores were deemed sufficient to meet the desired criteria for agreement because AC1 was higher than the preset threshold and other interrater metrics were in a range similar to that of metrics with TPA ≥ 80%. Failing this portion of the collision showed association with high magnitude accelerations in the tackler position for one rater (Rater 2, $p = 0.0272$) and but little evidence in the other (Rater 1, $p = 0.220$). Notably, similar trends are observed in both raters' distributions (Figure 3.3), but statistical significance was not seen with Rater 1's scores. Distributions showed no difference for either rater ($p \geq 0.283$).

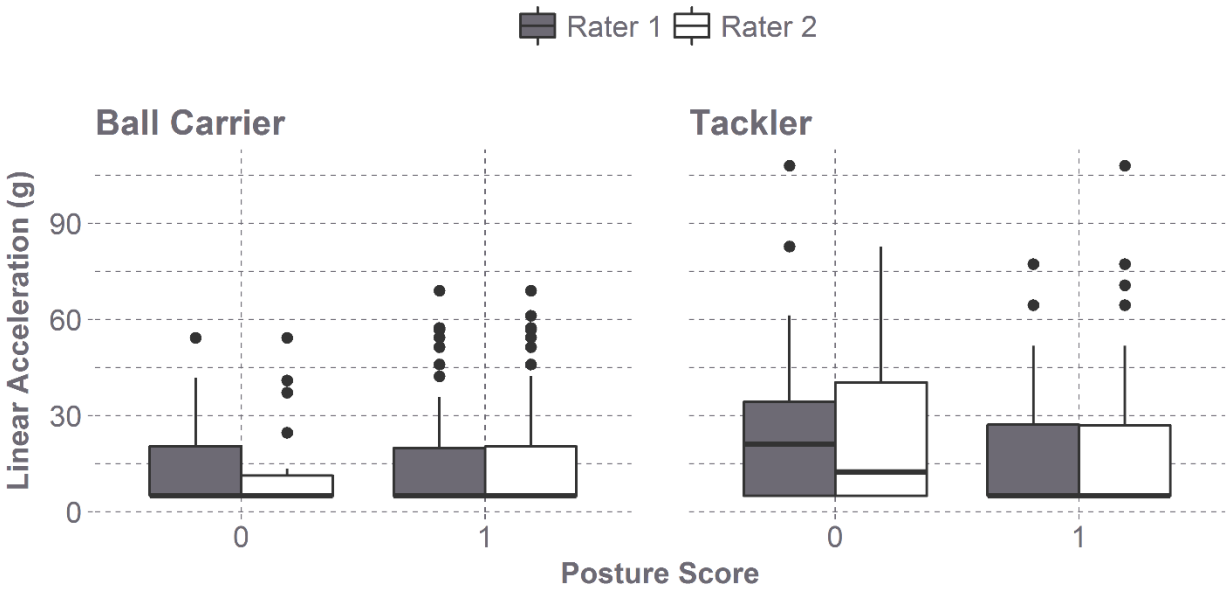

Figure 3.3: Boxplot showing Posture score for both positions in tackling drills. Failing this category showed association with high magnitude impacts for the tackler in Rater 2 but not in Rater 1. Distributions did not differ for either rater. 1 = Pass, 0 = Fail.

Line of Sight

The third category, *Line of Sight*, showed excellent TPA (87%) and met the criteria for AC1 (0.761). This agreement reflected in the fact both raters showed similar association between high magnitude head accelerations and failing scores for the ball carrier ($p \leq 0.033$) but not the tackler ($p \geq 0.534$) (Figure 3.4). Wilcox testing showed a difference in linear acceleration distributions for passing and failing scores in the ball carrier for Rater 2 only ($p = 0.021$, all other comparisons $p \geq 0.104$). A majority of failing scores (94%) were given due to the player looking toward the ground rather than toward his opponent or to the side during the tackle.

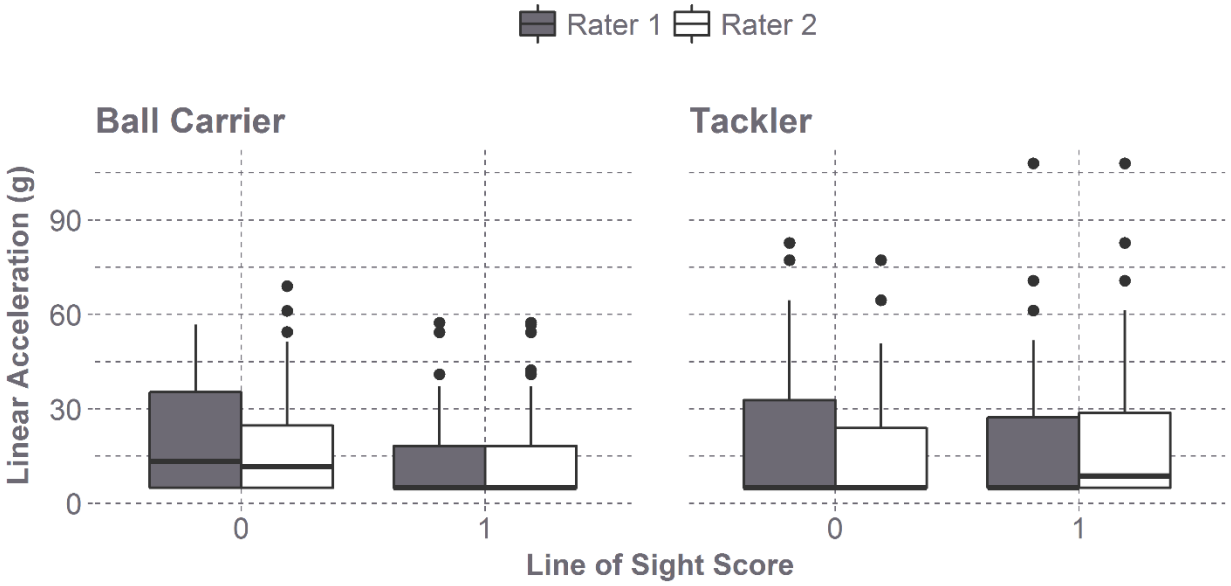

Figure 3.4: Boxplot showing Line of Sight score for both positions in tackling drills. Failing category showed association with high magnitude impacts for the ball carrier in both raters. Distributions differed for the ball carrier in Rater 2's scores. 1 = Pass, 0 = Fail.

Primary Contact

The *Primary Contact* category showed strong interrater reliability, with TPA of 80% and AC1 = 0.653. This category was deemed sufficient in agreement measures, and this conclusion was strengthened by the fact both raters showed evidence of association between failing scores and high magnitude acceleration outcome among tacklers. Both raters generated similar score distributions for the tackler, while Rater 1 ($p = 0.0518$) showed slightly stronger evidence of association with high magnitude acceleration than Rater 2 ($p = 0.0963$) (Figure 3.5). Distribution differences were significant for the tackler in both raters ($p \leq 0.048$) and for the ball carrier in Rater 1's scores ($p = 0.0007$) but not in Rater 2's scores ($p = 0.822$).

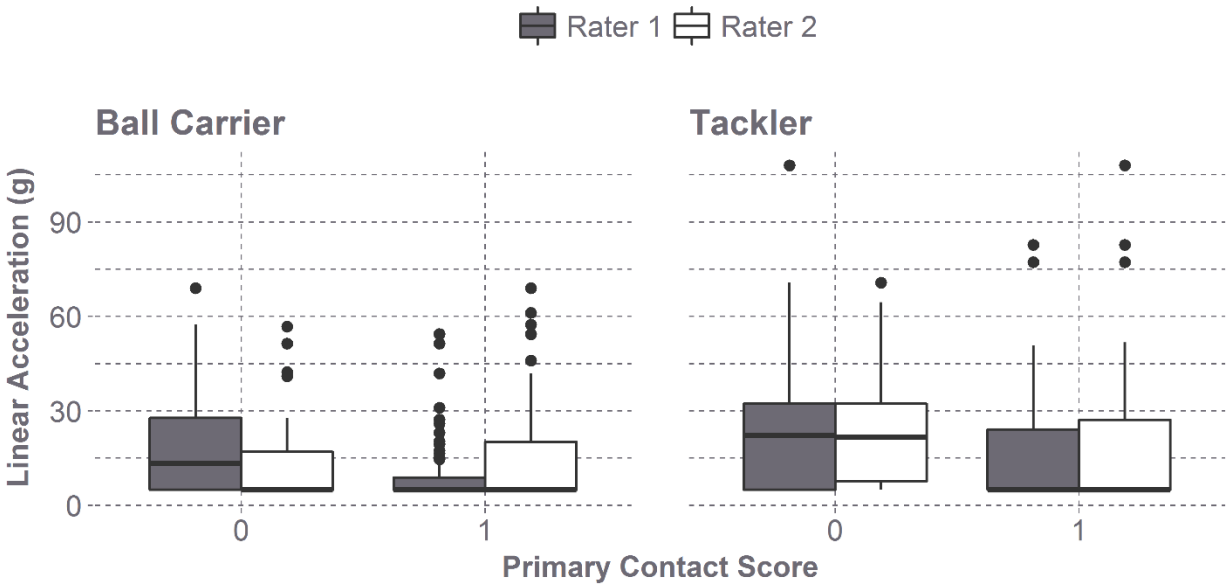

Figure 3.5: Boxplot showing Primary Contact score for both positions in tackling drills. Failing this category showed evidence of association with high magnitude impacts for the tackler in both raters' scoring. Distributions differed for both positions in Rater 1's scores and differed for the tackler in Rater 2's scores. 1 = Pass, 0 = Fail.

Initiation

The *Initiation* category exhibited the highest TPA (89%) and AC1 value (0.852), likely because of its extremely high proportion of positive agreement (P_{pos} = 0.934). Raters showed similar distributions (Figure 3.6) in scores for both positions. Scores from Rater 1 (p = 0.009) showed association between failing this category and experiencing a high magnitude acceleration as the tackler, while Rater 2's trend was similar but did not show the same strength of evidence for association (p = 0.194). Ball carrier scores did not show association between high magnitude acceleration and failing scores in this category for either rater ($p \geq 0.457$). Distributions were different for the tackler in Rater 1 (p = 0.0229) and showed evidence of difference for the ball carrier in Rater 2 (p = 0.0853), but did not differ otherwise ($p \geq 0.224$).

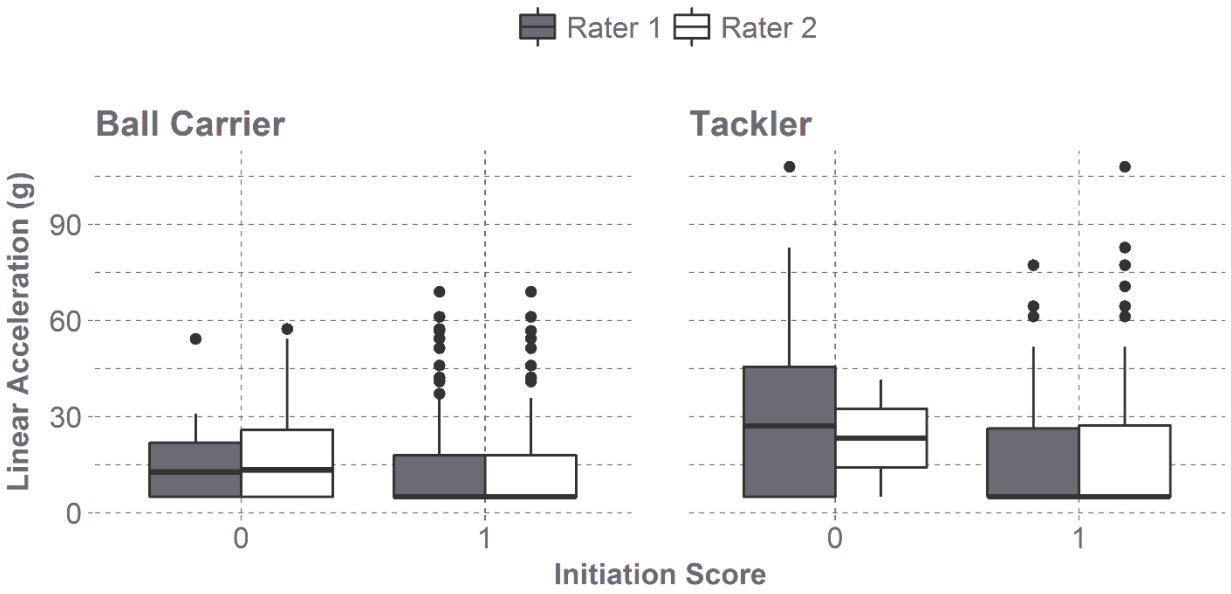

Figure 3.6: Boxplot showing Initiation score for both positions in tackling drills. Failing this category showed evidence of association with high magnitude impacts for the tackler in both raters. Distributions differed in the tackler with Rater 1's scores and showed evidence of difference in the ball carrier with Rater 2's scores. 1 = Pass, 0 = Fail.

Primary Contact Into

The tackler-only category of *Primary Contact Into* measured whether or not the part of the ball carrier that was contacted first influenced head acceleration outcome for the tackler. The intention here was to determine whether the tackler hit too high (head) or too low (knees). Interrater reliability measures were acceptable for this category (TPA = 83%, AC1 = 0.69). Scores from neither rater showed evidence of this category being associated with high magnitude acceleration in the tackler ($p \geq 0.177$) (Figure 3.7). Distributions for this category did not differ for either rater ($p \geq 0.308$).

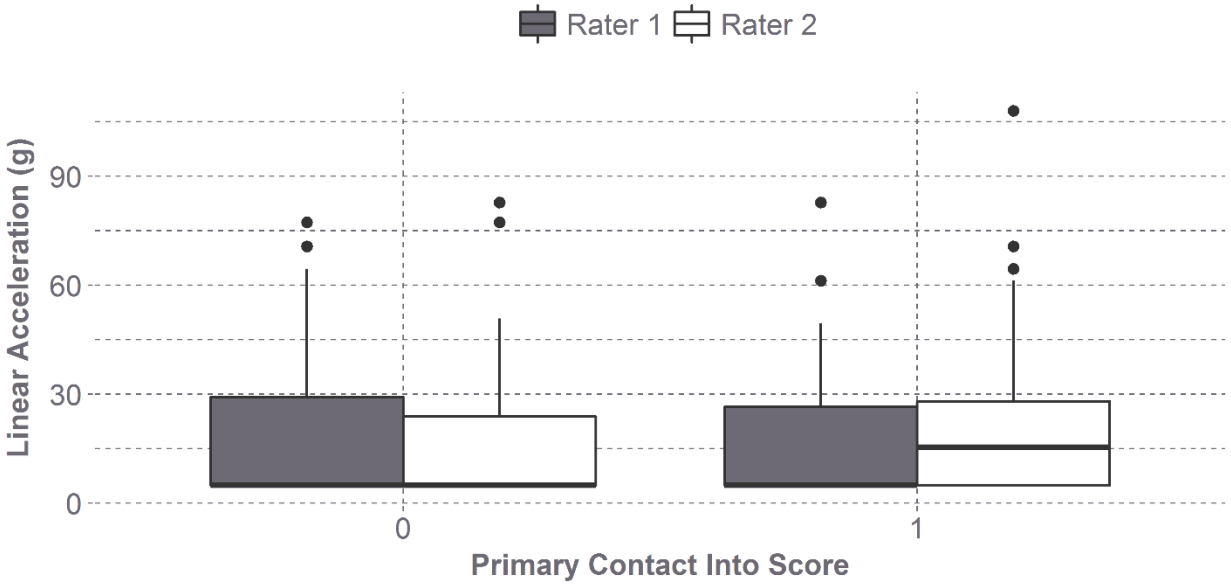

Figure 3.7: Boxplot showing Primary Contact Into score for the tackler in tackling drills. Failing this category showed no evidence of association with high magnitude impacts for the tackler in either raters' scores. Distributions for this category did not differ for either rater. 1 = Pass, 0 = Fail.

Ball Placement

The final category measured, *Ball Placement*, was intended to determine the extent to which a ball carrier protected his or herself, especially the torso region, by bracing for an impact. This category had high occurrence rates and good overall agreement (TPA = 87%), but zero agreement during non-occurrences. This category was found to be unassociated with high magnitude acceleration outcome in either rater ($p \geq 0.345$) (Figure 3.8). In addition, linear acceleration distributions did not show evidence of difference in Rater 1 ($p = 0.342$).

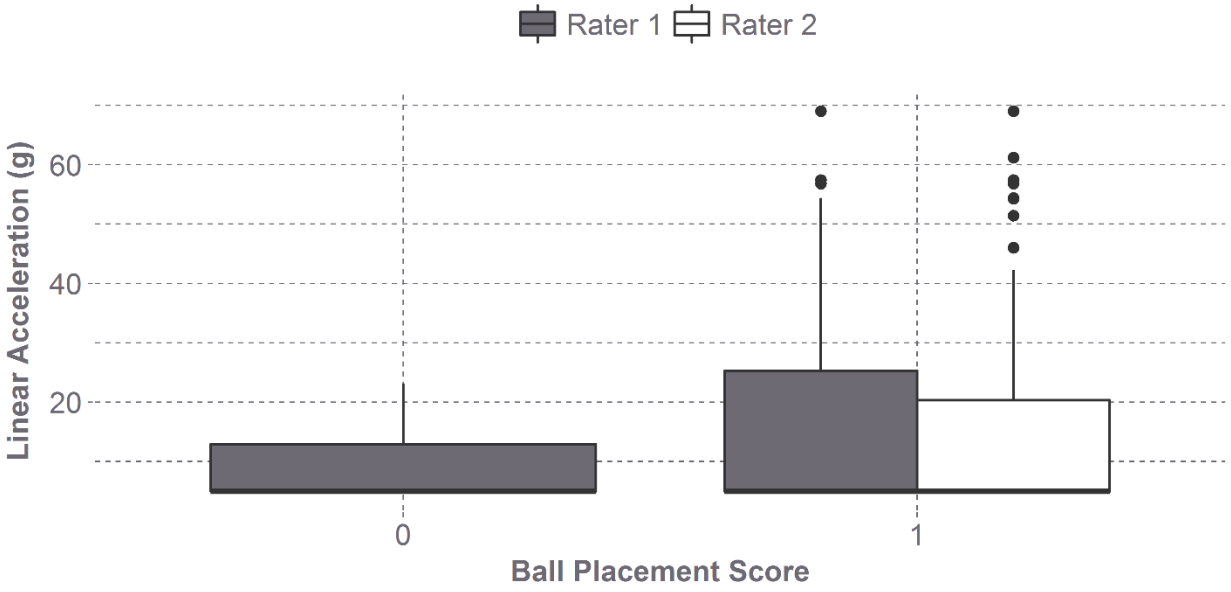

Figure 3.8: Boxplot showing Ball Placement score for the ball carrier in tackling drills. Failing this category showed no evidence of association with high magnitude impacts in either raters' scores. Distributions for this category did not differ for either rater. 1 = Pass, 0 = Fail.

Important Categories

Four of the six categories emerged as having evidence of association with high magnitude acceleration in at least one rater's score in individual impacts during tackling drills: *Posture* (Tackler), *Line of Sight* (Ball carrier), *Primary Contact* (Tackler), and *Initiation* (Tackler) (Figure 3.9). Three of these four categories were also found to differ in overall head acceleration distribution in at least one rater: *Line of Sight* (Ball carrier), *Primary Contact* (Tackler, Ball carrier), and *Initiation* (Tackler). Each of these categories exhibited high interrater agreement. Raters may have differed in their findings of association with high magnitude acceleration due to a difference in only a few ratings; after all, only one-tenth of the impacts had high magnitude accelerations in this dataset. When association was not found in one rater, the distribution of accelerations in his pass and fail bins showed similar trends with the other rater, in whose scores association was statistically significant. Wilcox testing confirmed differences in overall distributions of head acceleration between passing and failing scores in these same categories, except *Posture*.

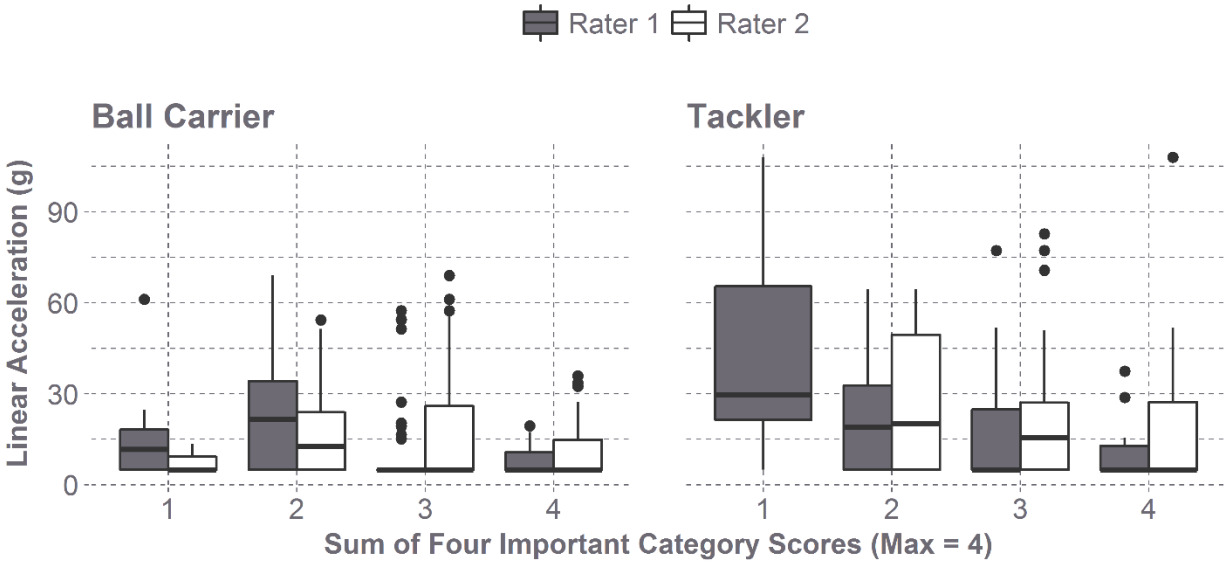

Figure 3.9: Boxplots showing sum of the four important category scores by position. Important categories were *Posture* (Tackler), *Line of Sight* (Ball carrier), *Primary Contact* (Tackler), and *Initiation* (Tackler). Tackles given higher scores, corresponding to better tackling form in important categories, showed the lowest acceleration distributions. Rater 1's scores are on the left, Rater 2's scores on the right.

Discussion

Despite the fact this cohort of youth football players had not been formally trained in any specific tackling program, technique varied widely across impacts. Receiving a low score as a ball carrier or a tackler did not guarantee experiencing a high magnitude acceleration, but chances of experiencing a high-risk impact were higher when a tackle with worse form was observed. This was similar across both position groups, though a greater number of categories showed association with high magnitude acceleration outcome in the tackler. Head acceleration distribution was seen to be different when receiving a passing score in three of the categories also displaying association with high magnitude accelerations.

The original criteria for scoring impacts was modified for use with multiple raters and afterward adjusted to improve interrater reliability. The original *Shoulder use* category was removed because it gave little new information past the *Primary Contact* category. Shoulder use was also difficult to grade reliably via video analysis due to camera angles. It may not be as important or reliable to train players to place their shoulder in a specific orientation because it may not be practical in some situations. Rather, shoulder use in general, instead of leading with the head, should be emphasized for every impact.

Balance, a part of a player's approach, was deemed insufficient in its interrater reliability. This category depended on raters being able to determine the placement and angle of players' feet directly before an impact, which was often difficult in certain videos. Foot placement could not be reliably graded with the methods used in this study. Neither raters' scores for this category showed association with high magnitude acceleration or difference in acceleration distribution. Some organizations stress foot placement for making a proper tackle, and this may have something

to do with successfully executing a tackle, but has little to do with preventing high-risk head impact exposure.

The last two categories, *Contact* and *Ball Placement*, showed sufficient interrater reliability, but did not show association with head acceleration outcome or differences in distribution. Ball placement, thought important for ball carriers' overall objective of advancing the ball down the field without losing possession, is not a determiner of head acceleration. Likewise, the part of the ball carrier that a tackler hits did not seem to affect whether or not the tackler or ball carrier saw a high magnitude acceleration. Though aiming a hit into a ball carrier's head or knees may prevent a tackler from executing a tackle, it does not appear to influence his or her head acceleration outcome.

The three most important categories for the tackler were *Posture*, *Primary Contact*, and *Initiation*. These categories represent a tackler bending at the hips and knees, leading with his shoulder pad or arm, and initiating contact rather than shying away. Proper posture in approaching a tackle likely sets up the remaining segments of that impact by allowing the tackler to brace for an impact without dropping his head (bending only at the hips) or sitting back on his heels (bending only at the knees). Using the shoulder or arm allows the tackler to keep his head away from the initial impact force. Though players did intentionally lead with the helmet at times, initiating contact gave the tackler the choice of which body part to lead with rather than being at the mercy of where the ball carrier decided to make contact with him. These three categories, when passed together, imply that the tackler was prepared for the impact and chose how to use his body during the impact by not leading with the head.

The ball carrier showed association with high magnitude acceleration only in the *Line of Sight* category, though the *Initiation* category also showed higher median accelerations for failing

scores than passing scores in both raters. Receiving a passing score in the *Primary Contact* category was seen to give a significantly different head acceleration distribution than receiving a failing score. The drills captured on film for use in this study were typically in small zones and controlled spaces. Ball carriers often did not need to look at the tackler to know where he would be. Designing drills in which ball carriers are required to look at their target could in turn lead to them keeping their head out of more plays by making them aware of their head's impending involvement (expecting the impact), keeping their head from being the first point of contact, and possibly keeping them from hitting tacklers' heads. In addition, ball carriers are not usually the subject of training in tackling programs. Thus, ball carriers may not have as much training on proper form (e.g. keeping their heads up) going into an impact.

It is interesting that ball carriers failing in the *Line of Sight* category did not correlate entirely with them failing in the *Primary Contact* category. This could be because ball carriers are typically trying to avoid the tackler, or glance off him, in order to continue past him. Ball carriers may be less apt to lead with their heads because of their objectives, but may still receive head impacts because they do not see the impact coming. Ball carriers may also receive head impacts when they are driven to the ground. Accelerations measured from being driven to the ground were not differentiated from accelerations caused by the first point of contact because the highest measured acceleration was chosen for each impact event.

Limitations of this study include the use of the same two expert raters for all grading. Interrater reliability was measured and showed good agreement between the two raters in this study, except in the *Balance* category. However, more raters may need to be used to effectively scale to all potential users for evaluating tackling form. Video quality also influenced some impacts, as different camera angles and lighting conditions were observed across the video records.

Having a set angle with each drill type (e.g. perpendicular to the plane of each impact) could help to standardize grading. Additionally, using two or more cameras to limit occlusions could eliminate choices of "Inconclusive" or guessing by raters. Finally, the tackles used in development and grading for this study were from a small sample of three teams over 10 different practice days. Future studies should investigate these trends across more teams over a longer period of time to confirm the findings in this study. Extensions of this study should also determine if players use similar form when engaging in collisions during games. Having been familiar with players in this study, the authors expect players to engage in similar tackling form during games.[26]

Conclusions

Technique during contact affects head acceleration outcome for both the tackler and ball carrier in youth football players during tackling drills in practice. Tacklers who exhibited proper posture, kept their head out of the impact and favored leading with their shoulder, and initiated contact rather than shying away had less chance of experiencing high magnitude impacts. Ball carriers who kept their eyes looking straight ahead or off to one side, without dropping their heads and taking their eyes off the tackler, showed the best outcome in head acceleration. This study demonstrates the potential effectiveness of training youth football players in tackling technique to reduce head acceleration exposure, but also shows a need for tackle absorption training for ball carriers, as well. This study does not endorse any specific tackling technique – each teaching style should be evaluated independently to determine its effectiveness in reducing head acceleration.

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CHAPTER 4

Method for Determining the Structural Response of Helmet Shells during Dynamic Loading

Abstract

Football helmet design and development involves changing a range of parameters including padding material and thickness, shell material and thickness, and padding location, all of which alter a helmet's dynamic response to impact. All of these parameters can affect performance of the helmets in conventional standards and supplemental testing. These parameters can be costly and time-consuming to change quickly during prototype development, and computational modeling of helmets helps to reduce both cost and time required. As one method of enabling helmet modeling for reduced prototyping time, full helmet models will need to be developed and validated with appropriate material characteristics. Most current material testing methods do not characterize response during real world loading conditions. We present a novel method for measuring the force-deflection characteristics of a football helmet shell using a pneumatic ram. This method involves a rigidly mounted helmet that is allowed to move along a single axis. Two accelerometers enabled the measurement of force and relative displacement, and tests were conducted in the range of 3 – 6 m/s input velocities for impacts to the front and side of the helmet. Data demonstrate repeatability at each impact configuration.

Introduction

Tensile or compressive testing machines are often used to determine mechanical properties of materials. These machines typically load the specimens at rates in the quasi-static range below 1 cm/s.[1] Small loading rates such as these can be orders of magnitude lower than loading rates seen in everyday use of these products. Ideally, the loading rates used in tests would coincide with the rates at which these products are used, as some rate dependency may exist. In addition,

appropriate modeling of these material properties can enable more accurate finite element modeling by validating model predictions against experimental results.[5]

Finite element modeling (FEM) of products enables designers to prototype and iterate efficiently. Recently, the National Football League's Engineering Roadmap spoke of FEM in football helmet development as one of the top priorities for driving new innovation in the field.[6] Force-deflection curves are commonly used in finite element model validation.[7] Previous studies have used FEM, validated by physical force-deflection tests, to characterize motorcycle helmet foam characteristics under both quasi-static and dynamic loading.[5] Each season, football helmets are subject to hundreds of impacts that occur to a number of different locations on the helmet and at a variety of severities.[3] Because football helmets are subject to dynamic loading events during their normal use, this study sought to present a novel experimental method for quantifying force-deflection characteristics of a helmet shell undergoing dynamic loading in two different orientations: front and side. It is expected these methods could be expanded to other loading orientations and severities across a range of helmet models.

Methods

The experimental setup consisted of a pneumatic ram (Biokinetics, Ottawa, Ontario, Canada) striking a helmet mounted to a custom bracket which was rigidly attached to a standard slider table. The slider table was allowed to move in the x-direction so that higher loading rates could be achieved. Velocities of 3, 4.5, and 6 m/s were chosen as test velocities. These speeds are representative of speeds used to test helmets in a lab environment and represent a range of energy inputs seen in contact sport impacts.[2,4,9,10] A custom impactor face was developed such that a single axis accelerometer could be mounted behind it, while the diameter and mass properties were maintained according to National Operating Committee on Standards for Athletic Equipment

(NOCSAE) standard 081-14m15.[8] Another single axis accelerometer was rigidly attached to the back of the custom bracket on which the helmet was mounted (Figure 4.1). The mass of the custom bracket and helmet assembly was approximately 21.2 kg; impactor mass was 15.56 kg as per NOCSAE standard.[8] A standard braking mechanism consisting of a metal cone, which progressively slows a large diameter rubber gasket attached to the impacting rod, was part of the pneumatic ram; however, complete disengagement of the impactor face from the helmet before engaging the built-in brake was verified for each orientation. This ensured energy transfer to only the helmet-slider system during each test.

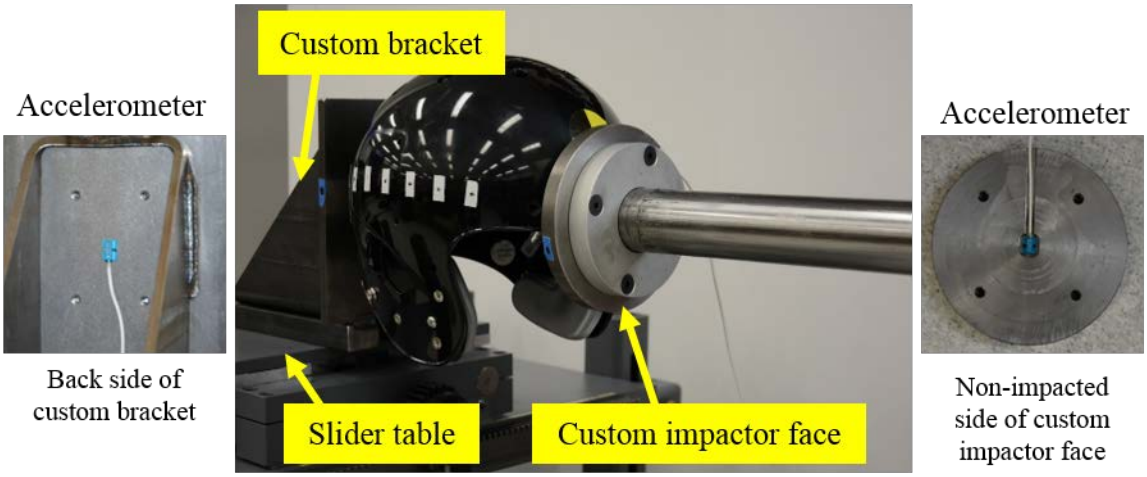

Figure 4.1: Experimental setup consisting of a linear impactor with custom face, bracket with attached helmet, slider table, and accelerometers mounted to impactor face and bracket. Positive sensing axes pointed away from the helmet for both the bracket-mounted and the impactor-mounted accelerometers.

One commercially available Schutt Air XP Pro model football helmet was used to evaluate the experimental design with five trials in each impact configuration. To mount the helmets to the flat bracket, the helmet shells were 3-D scanned, and a 3-D printed mount was developed which

enabled interface with both the curvature of the helmet and flat bracket. Different mounting pieces were used for the front and side locations to account for the different curvatures at these locations. The liner system was left in the helmets during testing, and was shifted as necessary to allow the mounts to couple to the helmets.

Impact locations were chosen to represent areas of the helmet shell that are commonly impacted during regular play.3 Front and side locations were defined from a reference point. The reference point is described by a point at which the helmet shell is mounted in the front orientation, is laterally centered with the impactor face, and at which the bottom lip of the foremost edge of the shell is even with the bottom of the impactor face (Figure 4.2). Both orientations were measured from this point and are pictured in Figure 4.3. Displacements from the zero point are listed for both test locations in Table 4.1.

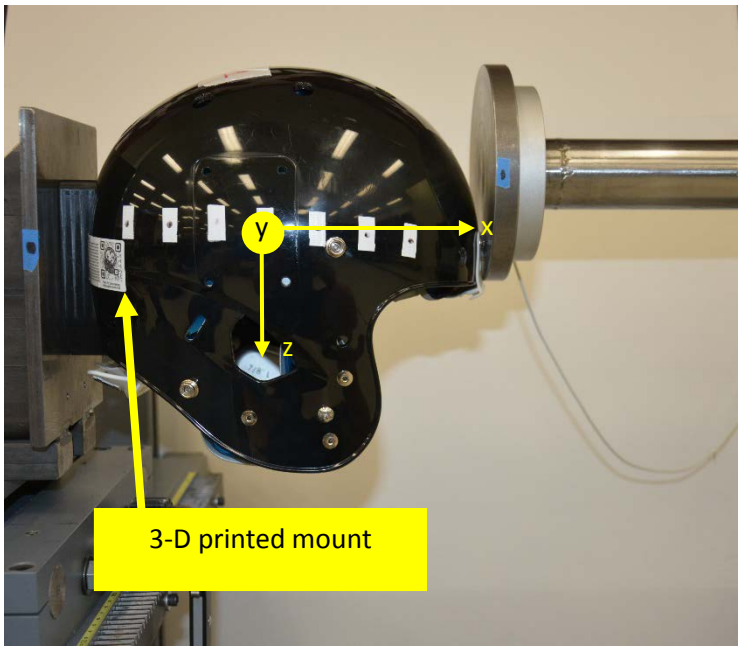

Figure 4.2: A zero location for the helmet was set to a point at which the helmet was centered with the impactor face laterally and the bottom lip of the foremost part of the helmet was aligned with the bottom of the impactor face. Z-axis is positive toward the bottom of the helmet, Y is positive out the right ear of the helmet (out of page), and X is positive toward the impactor face.

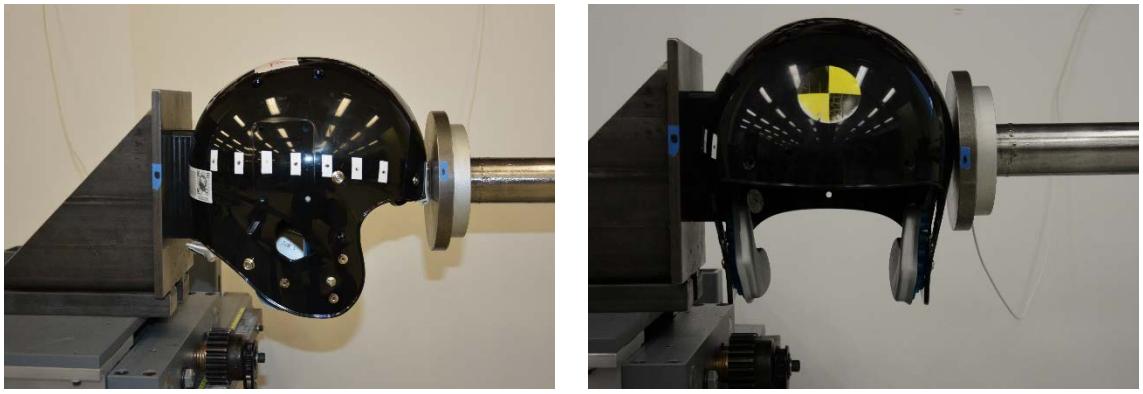

Figure 4.3: Front and side locations of the helmet for the experimental setup. Dimensions measured from the zero point are printed in Table 1.

Table 4.1: Offset dimensions from the zero point at each location used in experimental setup.

	y (cm)	z (cm)
Front	0	-6.4
Side	-0.6	-6.4

High-speed video of impacts were also taken using a Phantom Miro LC321S high speed camera (Vision Research, Inc., Wayne, NJ). All impacts were recorded at a framerate of 1000 Hz at resolution 1600 x 1200 pixels. These videos allowed visualization of helmet shell deflection.

Using a custom MATLAB (Mathworks, Natick, MA) code, both accelerometer signals were filtered at CFC 180. The acceleration of the impactor was multiplied by its mass to obtain impact force, and this signal was used to create the force-displacement curves, as there was less low-frequency noise in this signal than in the slider table signal. Acceleration traces were subtracted from one another and the resulting relative acceleration was integrated twice to obtain displacement. Initial velocity was estimated from a previously developed curve relating tank pressure to output velocity, as the impactor was stopped before the incorporated velocity gate could be used.

Results

Exemplary results are presented for each location and speed combination (Figures 4.4 and 4.5). Average peak helmet force and deflection values computed at the front and side locations are show in Table 4.2. Maximum coefficient of variation (COV) was 2.6% of peak force and 1.7% of peak deflection for the front orientation and was 4.0% of peak force and 1.7% of peak deflection for the side orientation, demonstrating a high degree of repeatability.

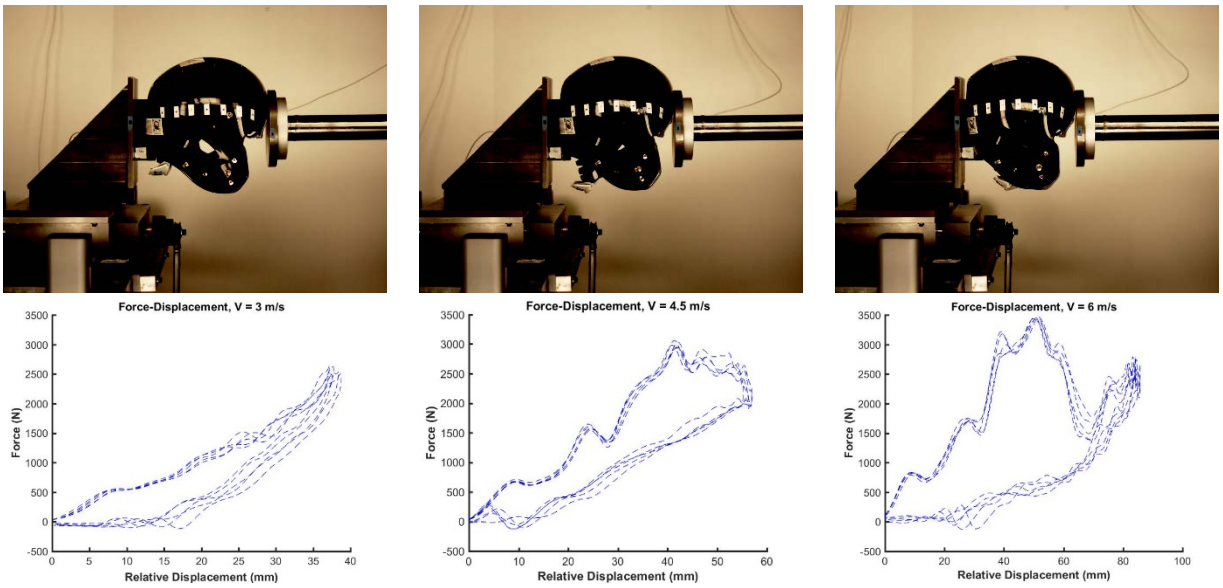

Figure 4.4: Representative test image and force-deflection curves for all five trials at each speed in the front location.

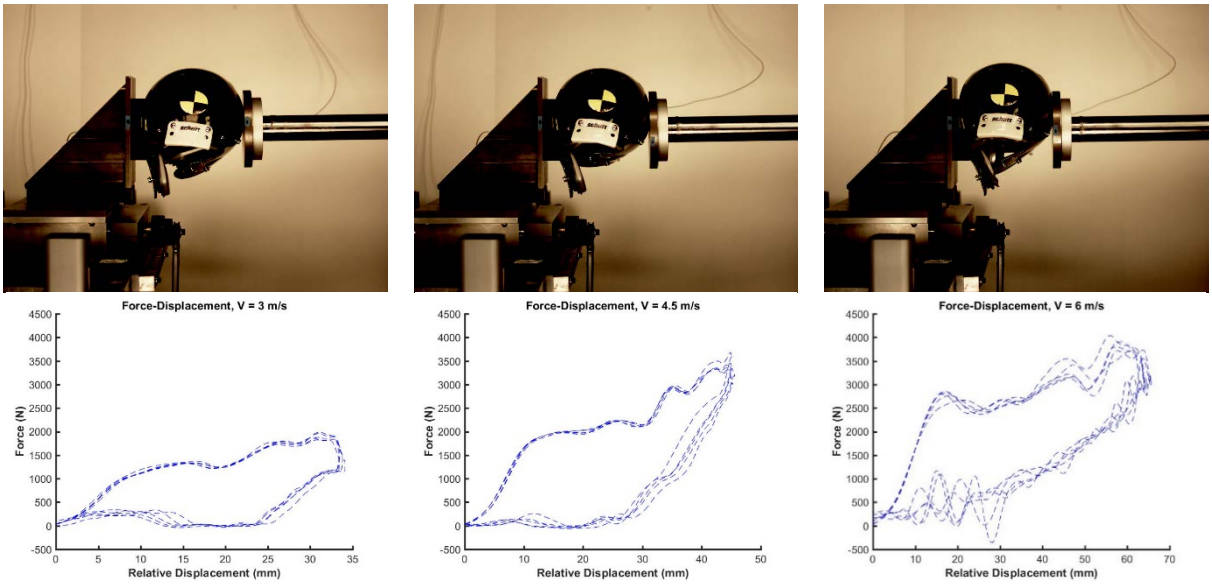

Figure 4.5: Representative test image and force-deflection curves for all five trials at each speed in the side location.

Table 4.2: Summary of average peak force and deflection values ± standard deviation for each location and test velocity. An increasing trend in both force and deflection was seen for increasing velocities at both locations. Repeatability was high, as standard deviations were observed to be low relative to average peak values.

Front	Average Peak Force (N) ± SD	Average Peak Deflection (mm) ± SD	**Side**	Average Peak Force (N) ± SD	Average Peak Deflection (mm) ± SD
3.0 m/s	2562 ± 66.0	37.94 ± 0.65	3.0 m/s	1906 ± 62.5	33.65 ± 0.30
4.5 m/s	2991 ± 53.5	56.46 ± 0.73	4.5 m/s	3451 ± 136.9	45.28 ± 0.18
6.0 m/s	3445 ± 21.5	85.12 ± 0.64	6.0 m/s	3836 ± 139.0	64.53 ± 1.09

Discussion

The experimental setup described enables dynamic loading of football helmets with high repeatability, as the COV of peak force and deflection across all tests was less than or equal to 4.0%. Consistency in curve shape and magnitude was likely due in part to the rigid attachment of the helmet to the bracket and slider assembly. This was enabled by the 3-D printed mounts, which matched the curvature of the helmet shells in their respective locations (rear or contralateral side – opposite the impact sites).

In future studies, this method could be used to test an entire helmet shell-liner system by rigidly attaching a headform to the slider table and fitting a helmet on this headform. This type of setup would leave the entire helmet liner intact for the tests and provide an even more realistic test condition, as football helmets are worn on a head during use. It will still be important to constrain the headform-helmet system to one-dimension of movement so that the force-deflection characteristics of the desired orientation are captured. This methodology can also be adapted to test helmets from a variety of other sports and helmet types. Testing such as this may be especially relevant for helmets designed to crush on impact, such as bike and some motorcycle helmets.

This study was limited by the use of one helmet shell of a single model. Other helmet models may not be as easily mounted to a bracket, and location of padding in other helmet models may make the use of the exact methods presented more difficult. In addition, an estimated force was calculated using the mass and measured acceleration traces. A load cell could theoretically be used in place of accelerometers to measure force directly, but would need to be inertially compensated. Finally, initial velocity used in the integration of acceleration curves was estimated from a previously validated correlation between tank pressure and output velocity of the specific impactor used for this test series.

Conclusions

A novel method for determining force-deflection characteristics of football helmets undergoing dynamic loading has been described. Illustrative data show force-deflection curves for the material and geometry with high repeatability in peak force and deflection values in six distinct test conditions. This method can be further developed in the future by modifying for multiple helmet types, directly measuring input velocity, and including other locations at which the helmet can be impacted. In addition, this method can also be modified to enable testing of an entire helmet-liner system so that finite element models of a range of helmet types can be validated. It is expected these data can inform finite element modeling by validating dynamic characteristics of football helmet models.

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CONCLUSIONS

Youth football head acceleration data revealed that team, position, and position within team were all significant factors in individual player head impact exposure. A player's role on the team (e.g. playtime) and the coaching style on that team also influence the frequency of head impacts experienced by members of a team. Some individual players are more prone to being involved in high magnitude impacts, and a small group is typically responsible for a majority of high magnitude impacts on any given team. Individual-specific interventions could reduce exposure to high magnitude head accelerations in practice for entire teams by as much as half.

Technique used during contact affects head acceleration outcome for both the tackler and ball carrier in youth players during tackling drills in practice. The most important aspects for a tackler are posture (bending at the hips and knees), keeping the head out of the tackle and leading with the shoulder or arm, and initiating contact rather than shying away. Ball carriers should keep their head and eyes looking forward, toward the tackler, or off to one side without looking down and taking their eyes off the tackler. Training youth players in proper form may be effective at reducing head acceleration exposure, so long as the training causes players to exhibit good form during tackling drills. Ball carriers, for whom no current recommendation exist, should be included in training for collision absorption – offensive players experienced just as many high magnitude accelerations as tacklers in graded impacts. This thesis did not investigate outcome measures tied to specific training programs; all training programs should be evaluated individually to determine effectiveness in reducing head acceleration.

Force-deflection characteristics of helmets under dynamic loading can be generated in a lab environment. The presented methodology could be modified in future experiments for different helmet types. Potential improvements could be made to this methodology by modifying

the 3-D printed mounts for multiple helmet types, directly measuring impact velocity, and including other orientations (e.g. top) in the test matrix.

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PUBLICATION PLANS

Chapter	Title	Journal
Ch. 1	Are Specific Players More Likely to be Involved in High Magnitude Head Impacts in Youth Football?	Submitted for review to *Journal of Neurosurgery, Pediatrics*
Ch. 2	Association Between Tackling Technique and Head Acceleration Magnitude in Youth Football Players	Accepted for presentation at the 2018 Rocky Mountain Bioengineering Symposium, to be published in Biomedical Science Instrumentation
Ch. 3	Does Tackling Form Affect Head Acceleration in Youth Football Players?	Submitted for review to *Journal of Neurosurgery, Pediatrics*
Ch. 4	Method for Determining the Structural Response of Helmet Shells During Dynamic Loading	Accepted for presentation at the 2018 Rocky Mountain Bioengineering Symposium, to be published in Biomedical Science Instrumentation

APPENDIX A

Using an example contingency table (Table A1), the formula for K is presented in Equations 1 through 1.4. Total percent agreement, though uncorrected for chance agreement, gives a summary of the amount of times raters agree overall (Equation 2). K is influenced by skew in rate of occurrence, which some believe is warranted.[8] However, AC1 was developed as a better summary metric for use when rates of occurrence are high or low.[16] This summary metric agrees well with K when rate of occurrence is equal (A = D), but differs purposely otherwise (Equations 3 – 3.2). Finally, arguments for using K alongside other metrics have advocated the reporting of proportion of positive and negative agreements (P_{pos} and P_{neg}).[8] These statistics reveal the source of disagreement (if present) better than a single summary statistic by reporting the rate of agreement in positive (or negative) occurrence as a proportion of all raters' reporting of positive (negative) occurrence. Equations 4 and 5 show how to calculate P_{pos} and P_{neg}.

Table A1: Example of contingency table for two independent raters. Letters A-D represent number of times raters agreed or disagreed and are used in the following equations to demonstrate each statistical reliability measure presented.

		Rater 1	
		Pass	Fail
Rater 2	Pass	*A*	*B*
	Fail	*C*	*D*

$$K = \frac{P_o - P_e}{1 - P_e}, \text{ where} \quad (1)$$

$$P_o = \frac{A+D}{A+B+C+D} \quad (1.1)$$

$$P_e = P_{yes} + P_{no} \tag{1.2}$$

$$P_{yes} = \frac{A+B}{A+B+C+D} * \frac{A+C}{A+B+C+D} \tag{1.3}$$

$$P_{no} = \frac{C+D}{A+B+C+D} * \frac{B+D}{A+B+C+D} \tag{1.4}$$

$$TPA = \frac{A+D}{A+B+C+D} * 100\% \tag{2}$$

$$AC1 = \frac{P_o - P_e^*}{1 - P_e^*}, \text{ where} \tag{3}$$

$$P_e^* = 2 * \Pi * (1 - \Pi) \tag{3.1}$$

$$\Pi = \frac{1}{2} * (\frac{A+C}{A+B+C+D} + \frac{A+B}{A+B+C+D}) \tag{3.2}$$

$$P_{pos} = \frac{2*A}{2*A+B+C} \tag{4}$$

$$P_{neg} = \frac{2*D}{2*D+B+C} \tag{5}$$