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Biomechanical assessment of in-game North American youth football helmet impacts using a multi-camera video-based methodology

By

Danielle Gyemi

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Biomechanical assessment of in-game North American youth football helmet impacts using a multi-camera video-based methodology

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DECLARATION OF CO-AUTHORSHIP / PREVIOUS PUBLICATION

I. Co-Authorship

I hereby declare that this thesis incorporates material that is result of joint research, as follows: Chapters 2 and 4 were co-authored with Dr. Ron Jadischke (Special Committee Member) and Dr. David M. Andrews (Advisor). In both cases, the key ideas, primary contributions, experimental designs, data analysis, interpretation and writing were performed by Danielle L. Gyemi. The contribution of the co-authors was primarily through the provision of critical feedback on the refinement of ideas and interpretation of study results, and assisting with editing the manuscript. Chapter 3 was co-authored with Claudia M. Town, Yousef J. Alami, Dr. Ron Jadischke and Dr. David M. Andrews. The key ideas, primary contributions, experimental designs, data analysis, interpretation and writing were performed by Danielle L. Gyemi. Co-authors Claudia M. Town and Yousef J. Alami assisted with the data analysis and review of the manuscript. Co-authors Dr. Ron Jadischke and Dr. David Andrews contributed primarily through the provision of critical feedback on the refinement of ideas and interpretation of study results, and assisted with the editing of the manuscript. Dr. Ron Jadischke is employed by Xenith, a manufacturer of helmets, gear and apparel for American football and related sports, who contributed the equipment and software necessary to conduct the research across Chapters 2, 3 and 4.

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II. Previous Publication

This thesis includes three original papers that have been previously published/submitted to journals for publication, as follows:

Thesis Chapter	Publication title/full citation	Publication status*
Chapter 2	Gyemi, D. L., Andrews, D. M., & Jadischke, R. (2021). Three-dimensional video analysis of helmet-to-ground impacts in North American youth football. *Journal of Biomechanics, 26*(125), 110587. http://doi.org/10.1016/j.jbiomech.2021.110587	*Published*
Chapter 3	Gyemi, D. L., Town, C. M., Alami, Y. J., Jadischke, R., & Andrews, D. M. (2022). A descriptive video analysis of helmet impact cases in North American youth football players.	*Submitted*
Chapter 4	Gyemi, D. L., Jadischke, R., & Andrews, D M. (2022). Validation of a multi-camera videogrammetry approach for quantifying helmet impact velocity in football.	*Submitted*

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ABSTRACT

Video analysis has played a key role in studying the biomechanics of in-game helmet impacts in football, both descriptively and quantitatively. To date, this work has primarily focused on concussive impacts in National Football League games due to the availability of high-quality, multi-view video for assessment (e.g., broadcast footage). Research efforts aiming to understand helmet impact biomechanics of untelevised youth football populations (≤ 14 years) have mostly relied on sensor-driven data from instrumented helmets. A few studies have used a single-camera system; however, this limits the data that can be obtained. The purpose of this dissertation was to develop, validate and apply a multi-camera approach (adapted from Jadischke et al. (2020)) to assess the biomechanics of helmet impacts in youth football games using descriptive and quantitative video analysis techniques. The overall goal of this research was to contribute to athlete safety improvements and inform youth-specific helmet test standards and design. These objectives were accomplished in three empirical studies. Study 1 (Chapter 2) used a videogrammetry approach to quantify three-dimensional (3D) helmet velocities of 21 non-injurious helmet-to-ground (H2G) impact cases identified from three youth football games (game A: 9–12 years; games B and C: 13–14 years). Contact progressions of these cases mostly involved a body-to-body and body-to-ground contact, followed by a rear or side helmet strike with the ground. Resultant pre-impact velocities averaged 4.04 ± 1.24 m/s at an angle of -49.6° to the field. The average resultant impact-induced change in helmet velocity was 3.32 ± 1.14 m/s; the approximate time interval of the duration of H2G contact was

0.06 s. In Study 2 (Chapter 3), a descriptive video analysis of the mechanisms and situational factors associated with helmet impact cases from the three youth football games was performed. The multi-view game video was reviewed and parameters related to all cases of observed helmet impact (injury and non-injury) were documented. Overall, the majority of cases occurred during a rush play (67.4%) and were concentrated in the mid-field (81%). Helmet-to-ground contacts were most common (59.1%) and contact locations were predominantly distributed across the rear (upper) (28.7%) and side (upper) (27.8%) helmet regions. Tackling was the most frequent activity leading to helmet impact (41.1%). The aim of Study 3 (Chapter 4) was to confirm the validity of the videogrammetry approach for measuring 3D helmet impact velocities in football by determining the effect of camera angle, camera distance and impact speed. A series of slow (1.04 m = 4.52 m/s) and fast (1.83 m = 5.99 m/s) free fall drop tests were conducted using a helmeted anthropomorphic test device head and neck assembly to simulate H2G impacts within two different zones on a football field. Helmet motion was tracked using 3D motion analysis software across different camera view combinations (orthogonal, coincident, overhead, parallel) for each zone, and resulting helmet velocities were computed. In general, the results showed the effectiveness of several camera angles (except parallel) for measuring 3D helmet impact velocity; increased camera distance and impact speed did not appreciably influence video tracking accuracy. Lastly, Chapter 5 explored the methodological considerations (e.g., equipment, input/output parameters) of accurately conducting laboratory reconstructions of H2G impacts for youth football players.

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2D – Two-dimensional

3D – Three-dimensional

AE – Absolute error

B2B – Body-to-body

B2G – Body-to-ground

H2B – Helmet-to-body

H2G – Helmet-to-ground

H2H – Helmet-to-helmet

NOCSAE – National Operating Committee on Standards for Athletic Equipment

MBIM – Model-based image-matching

RE – Relative error

RMSE – Root-mean-square error

CHAPTER 1

BACKGROUND AND SIGNIFICANCE

General Introduction

The study of head impacts in sport and recreation is very prevalent in biomechanics research, especially in the context of football[1]. Given the high-contact nature of the sport, exposure to head impacts[2] and associated brain injuries is an inevitable risk for participating players, which is reflected in its ranking as one of the top team sports for concussion incidence across different age and skill levels (Kerr et al., 2017, 2019; Marshall et al., 2015; Pfister et al., 2016; Zuckerman et al., 2015). Although concussion in football is a primary concern among researchers and clinicians (Dompier et al., 2015), there is increasing evidence suggesting that repetitive exposure to sub-concussive head impacts accumulated over years of contact sport participation may result in debilitating long-term neurocognitive or neuropsychiatric consequences, even with no history of concussion (Huber et al., 2016). Studies on former professional players have shown that exposure to football before the age of 12 years is likely connected to impaired cognitive functioning later in life along with alterations in the microstructure of the brain white matter (Stamm, Bourlas et al., 2015; Stamm, Koerte et al., 2015). The same outcome was also observed in a separate sample of former male professional and amateur (i.e., high school and collegiate) football players regardless of player age, years of education and duration of play (Alosco et al., 2017). Considering that there are as many as 2.3 million American (The Aspen Institute, 2020) and 100 thousand Canadian

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[1] The word "football" refers to North American tackle football

[2] When used in the context of football, the term “head impact(s)” or “head contact(s)” refers to a helmeted head being impacted.

(Bromberg, 2019) youth football players in North America, understanding the underlying biomechanics of head impacts in this population is critical to improving the safety of the sport for participating athletes.

Risk Factors for Youth Players

Differences in the physicality of youth compared to adults, such as increased head-to-body ratio as well as reduced neck strength and musculature, may predispose this population to head injury (i.e., concussion) as they are limited in their capacity to counter sudden head accelerations from an impact event (Buzzini & Guskiewicz, 2006; Collins et al., 2014). It has been posited that this can be further exacerbated by the mass of the helmet in proportion to youth body size, especially for younger players 5 to 9 years of age (Kuhn et al., 2017). Alternatively, from a neurophysiological standpoint, the ongoing myelination of the youth brain as it fully develops may lead to an elevated risk of shear strain in response to impact (Choe et al., 2012; Karlin, 2011). Concussion risk functions have reported lower injury tolerances for peak head accelerations in youth (62.4 ± 29.7 g and 2609 ± 1591 rad/s^2) compared to adult (102.5 ± 32.7 g and 4412 ± 2326 rad/s^2) football players, supporting the notion that these factors may contribute to an increased concussion susceptibility among youth (Campolettano et al., 2020); although, the validity of the sensor data used to derive these functions has been questioned (Jadischke et al., 2013; Joodaki et al., 2019). Nonetheless, it is evident that further investigation of the biomechanical responses associated with head impacts experienced in the youth football population is warranted.

Methods of In-Game Helmet Impact Assessment

Sensor-based methods

With the mechanism of brain injury believed to be linked to rapid accelerations of the head following a direct or indirect impact (King et al., 2003), significant effort has been dedicated towards establishing methods that can quantify the kinematics of the head during real-world impact events. Advancements in wearable technology have introduced several different types of sensor-based methods capable of estimating head accelerations during sport participation (Patton, 2016). Research efforts over the last decade targeting youth football populations (≤ 14 years old) have mainly focused on sensor-driven data from instrumented helmets (e.g., the Head Impact Telemetry (HIT) System) that consist of a series of accelerometers mounted to the interior of the helmet shell (Duma et al., 2005; Rowson et al., 2011). Head impact exposure data obtained from these devices have illustrated key trends, such as an increase in impact magnitude (i.e., head acceleration) and frequency with increased player age and level of play (Table 1.1) (Campolettano et al., 2017; Cobb et al., 2013; Daniel et al., 2012, 2014; Kelley, Kane, et al., 2017; Kelley, Urban, et al., 2017; Munce et al., 2015; Young et al., 2014). However, the validity of these devices to provide accurate measures of head impact severity has been shown to be questionable, especially due to the relative motion that occurs between the helmet and head during a football impact (Jadischke et al., 2013; Joodaki et al., 2019). For instance, preliminary studies for the HIT system reported less than 10 % error between helmet and head accelerations (Manoogian et al., 2006), yet work by Joodaki et al. (2019) demonstrated noticeably clear helmet translation and rotation with respect to the head during a simulated football impact, wherein peak resultant helmet accelerations were 2 to 5 times higher compared to the head.

Table 1.1 – Summary of head impact exposure data from instrumented helmets in youth football on a per season basis (≤ 14 years old).

				Linear acceleration (g)		Angular acceleration (rad/s^2)	
Authors	Method	Level of play	Impacts per season	Median (50%)	95%	Median (50%)	95%
Daniel et al. (2012)	HITS	7–8 years	107	15	40	671	2347
Young et al. (2014)	HITS, 6DOF	7–8 years	161	16	38	686	2052
Cobb et al. (2013)	HITS	9–12 years	240	18	43	856	2034
Kelley, Urban et al. (2017)	HITS	10.8 ± 0.7 years	331	20	49	958	2323
		11.9 ± 0.5 years	333	21	51	980	2416
		13.0 ± 0.5 years	364	22	58	992	2544
Munce et al. (2015)	HITS	11–13 years	252	20	57	1407	3929
Daniel et al. (2014)	6DOF	12–14 years	275	22	60	987	2796

Video-based methods

Compared to using sensor-based methods to assess the biomechanics of head impacts occurring in youth football games, video-based methods have been applied, but to a much lesser extent and with a limited level of accuracy. Review of the literature has shown that the most common application of video in youth football studies is solely to verify sensor recorded impacts from instrumented helmets (Cobb et al., 2013; Daniel et al., 2012, 2014; Kelley, Kane, et al., 2017; Kelley, Urban, et al., 2017; Young et al., 2014). Few studies have used video as a tool to supplement sensor-driven data from youth football players, either through describing the on-field characteristics (Alois et al., 2019; Campolettano et al., 2017; Le et al., 2021) or quantifying helmet velocities (Campolettano et al., 2018) associated with head impact. However, single-camera systems were employed in these studies, which limit the detail of the descriptive data that can be obtained and, more importantly, reduce the accuracy of calculated helmet impact kinematics (i.e., velocity) since three-dimensional (3D) motion must be reconciled as position changes in two-dimensional (2D) space.

In contrast, video-based methods have been influential in the assessment of head impacts in the National Football League (NFL), especially those resulting in concussion. This is likely due to the high-quality, multi-view video available at the professional level from network broadcast footage (as well as other non-broadcast sources), whereas youth competitions are largely untelevised. Descriptive video analyses have been performed across several NFL seasons to contextualize the game situations and mechanisms of reported concussive events (Clark et al., 2017; Lessley et al., 2018). Taking advantage of the multiple camera views, these studies were able to document several key impact details including, but not limited to: play type (rushing, passing, etc.), time of game, field location, impact type (helmet-to-helmet, helmet-to-ground, etc.), helmet contact location, activity leading to helmet impact, etc. These concussion scenarios have been further characterized according to specific player positions (e.g., quarterback, running back, safety, etc.) to demonstrate how the circumstances of injurious impact exposures can differ by the position played (Lessley et al., 2020).

In addition to the descriptive data, various video analysis techniques that employ videogrammetry (i.e., the process of calculating 3D coordinates from measurements taken in two or more 2D video images) have also been applied in the NFL to measure 3D helmet kinematics of concussive impacts. Pellman et al. (2003) quantified the closing velocity of 31 severe impacts and concussions between the 1996 to 2001 NFL seasons using a previous analytical approach (Newman et al., 1999; Newman et al., 2000). More recently, a model-based image-matching (MBIM) technique developed by Bailey et al. (2018) has been used to compute the position and orientation of the helmet during concussive NFL game impacts in all six degrees of freedom (Bailey et al., 2020; Kent et al., 2020). It is important to note, however, that any kinematic measurements extracted from the video analysis of helmeted sports such, as football, will correspond to tracking of the helmet (i.e., not head) motion (Bailey et al., 2018).

Football Helmet Test Standards

Performance testing and certification of all football helmets is completed by the National Operating Committee on Standards for Athletic Equipment (NOCSAE). Originally, the NOCSAE football helmet standard utilized only linear head acceleration to evaluate football helmet performance with the same test protocols applied across all football populations, from youth to adult, regardless of player size. The most recent modifications and revisions to the standard for newly manufactured football helmets have seen the inclusion of pass/fail specifications for rotational head accelerations to better address concussion risk (NOSCAE, 2017). A separate standard for youth football helmets has also recently been proposed (NOCSAE, 2020); however, there remains insufficient data to support that the severity of the impact tests in the standard are representative of the on-field impact conditions that youth players are exposed to in competitions.

Specific Aims

The key motivation backing the work in this dissertation is that, of the limited biomechanical research on helmet impacts in youth football, a significant proportion is founded on sensor-driven data, while research in professional football has demonstrated the value of using video as a tool for understanding the mechanics of helmet impact. The overarching aim of this dissertation was to develop, validate and apply a multi-camera approach (adapted from (Jadischke et al., 2020)) to assess the biomechanics of in-game youth football helmet impact through descriptive and quantitative video analysis techniques. The overall goal of the research is to contribute novel information to the literature on helmet impacts experienced by youth football players that will facilitate ongoing efforts to improve athlete safety and protection; in particular, the advancement of youth-specific football helmet test standards and helmet design.

The specific aims of each chapter are outlined below:

> **Chapter 2 –** To quantify 3D helmet velocities associated with helmet-to-ground impact cases observed in youth football games using a videogrammetry approach.
>
> **Chapter 3 –** To assess the situational factors and mechanisms of helmet impacts observed in youth football games using descriptive video analysis.

Chapter 4 – To assess the effect of camera angle, camera distance and impact speed on the validity of the aforementioned videogrammetry approach for measuring 3D helmet impact velocities in football.

Chapter 5 – To explore and elucidate the challenges of accurately conducting laboratory reconstructions of real-world helmet-to-ground impact cases experienced by youth football players.

Dissertation Overview

The data presented in Chapters 2, 3 and 4 of this dissertation were structured as a series of manuscripts for three separate empirical studies related to different aspects of using video analysis to investigate helmet impacts in youth football; these chapters are organized in the order of publication appearance. Chapter 5 presents a theory-based discussion on the methodological considerations for the physical reconstruction of youth football helmet impacts, based on the findings from Chapter 2. Figure 1.1 provides an overview of the dissertation research, depicting the general progression of the work for Chapters 2 through 5. Lastly, a summary of the research, key findings of each study and potential directions of future work are provided in Chapter 6.

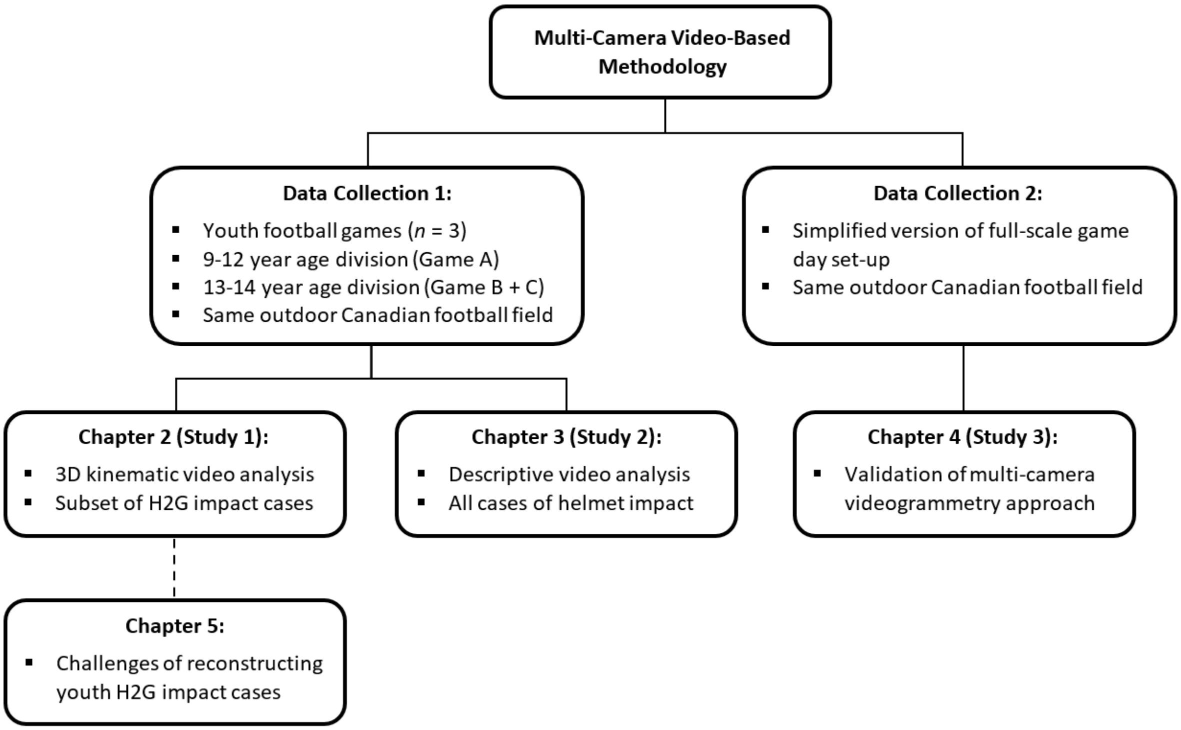

Figure 1.1 – Flowchart depicting an overview of the dissertation research (H2G = helmet-to-ground).

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CHAPTER 2

THREE-DIMENSIONAL VIDEO ANALYSIS OF HELMET-TO-GROUND IMPACTS IN NORTH AMERICAN YOUTH FOOTBALL[3]

Introduction

Until recently, helmets for youth football players were certified through the National Operating Committee on Standards for Athletic Equipment (NOCSAE) using the same impact testing protocols originally developed for adult football players (NOCSAE, 2011). NOCSAE has since proposed a new standard specific to youth football helmets (NOCSAE, 2020); however, it remains unclear how well the severity of impacts in the standard represents the actual impact conditions experienced on-field by youth players. Work in this area has been largely dominated by the use of instrumented helmets equipped with helmet-mounted accelerometer arrays to assess real-time head impact exposure across various youth football populations (≤ 14 years) (Campolettano et al., 2017; Cobb et al., 2013; Daniel et al., 2012, 2014; Kelley, Kane, et al., 2017; Kelley, Urban, et al., 2017; Munce et al., 2015; Young et al., 2014). Despite notable limitations regarding the validity of such devices (Jadischke et al., 2013; Joodaki et al., 2019), data collected using instrumented helmets continues to drive our knowledge of head impact biomechanics in youth football (Campolettano et al., 2020).

While not as extensively used, video analysis methods have been employed in football as an independent means to quantify in-game head impact velocities (Bailey et al., 2020; Kent, Forman, Bailey, Funk et al., 2020; Pellman et al., 2003). Laboratory

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reconstructions have been conducted from this data to measure the head accelerations resulting from these impact parameters (Kent, Forman, Bailey, Funk, et al., 2020; Pellman et al., 2003). The focus of this research has mostly been limited to injurious (i.e., concussive) impacts amongst National Football League (NFL) players. Pellman et al. (2003) utilized a three-dimensional (3D) video analysis methodology (Newman et al., 2000; Newman, et al., 1999) to analyze the kinematics of 31 severe head impacts (27 helmet-to-helmet (H2H), 4 helmet-to-ground (H2G)) from NFL game videos spanning 1996 to 2001, wherein concussive impacts had an average closing velocity of 9.3 ± 1.9 m/s. More recently, Kent, Forman, Bailey, Funk, et al. (2020) and Bailey et al. (2020) applied a model-based image-matching (MBIM) approach (Bailey et al., 2018) to examine the biomechanics of concussive NFL game impacts. In this dataset, video analysis of H2G impacts resulted in an average closing velocity of 8.3 ± 1.9 m/s; the average change in velocity of the head during these ground impacts was 8.1 ± 1.7 m/s. Impact locations for these H2G concussions were predominantly to the rear and side of the helmet, reflecting the findings of previous descriptive video analysis work (Lessley et al., 2018).

With respect to youth football, any form of video analysis that has been used to investigate head impact biomechanics is often delegated to the secondary role of confirming sensor-recorded impacts from instrumented helmets (Campolettano et al., 2017; Cobb et al., 2013; Daniel et al., 2014; Kelley, Kane, et al., 2017; Kelley, Urban, et al., 2017; Young et al., 2014). To the author’s knowledge, only one study by Campolettano et al. (2018) has attempted to measure head impact velocity from video recordings of youth football games; however, this analysis was conducted with a single camera view which limits the accuracy of calculating pre-impact velocity and does not allow for the calculation of change in velocity since these are both vector quantities. Furthermore, only impacts involving H2H contact between two players were assessed.

There is a paucity of research on the use of video to analyze head impact biomechanics in youth football, with no information currently existing for H2G impacts. The present study aimed to analyze the in-game biomechanics of H2G impact cases in youth football (≤ 14 years) using a novel video-based methodology to estimate 3D pre-impact velocities and impact-induced change in velocity, and describe the mechanisms of impact. The findings from this work may assist in implementing a more representative standard for youth football helmet testing.

Methods

In-game video data collection

The data collection methodology used in the present study was adapted from recent video analysis work by Jadischke et al. (2020) that used a multi-camera approach to assess head impact biomechanics in un-helmeted youth and varsity-aged players in non-tackle American 7v7 football. Game video was recorded for three youth football games across two age divisions: one game for a 9–12 year age division and two games for a 13–14 year age division. The games took place between November 2018 and July 2019 at the same outdoor Canadian football field with artificial turf (CORE system, installed 2008; FieldTurf Inc., Montreal, QC, Canada).

Eleven action cameras (HERO6; GoPro, Inc., San Mateo, CA, USA) with 41° field of view (FOV) lenses recorded video at 2.7K resolution and 120 frames per second (fps) with a shutter speed of 1/1920 s; these camera settings align with prior validation analysis (Jadischke et al., 2019). The cameras were stationary and positioned at locations around half of the field of play with four cameras along each side line at 15-yard intervals and three cameras across the back of the end zone (Figure 2.1). An additional camera (4K/60 fps) with a wide-angle lens (120° FOV) and shutter speed of 1/960 s was used for the 13–14 year age division games, providing an overall view of the field. Camera times were manually synchronized using an external clock to match the time of day within a few seconds. Calibration images were also captured from each camera view to set the 3D field coordinate system during analysis.

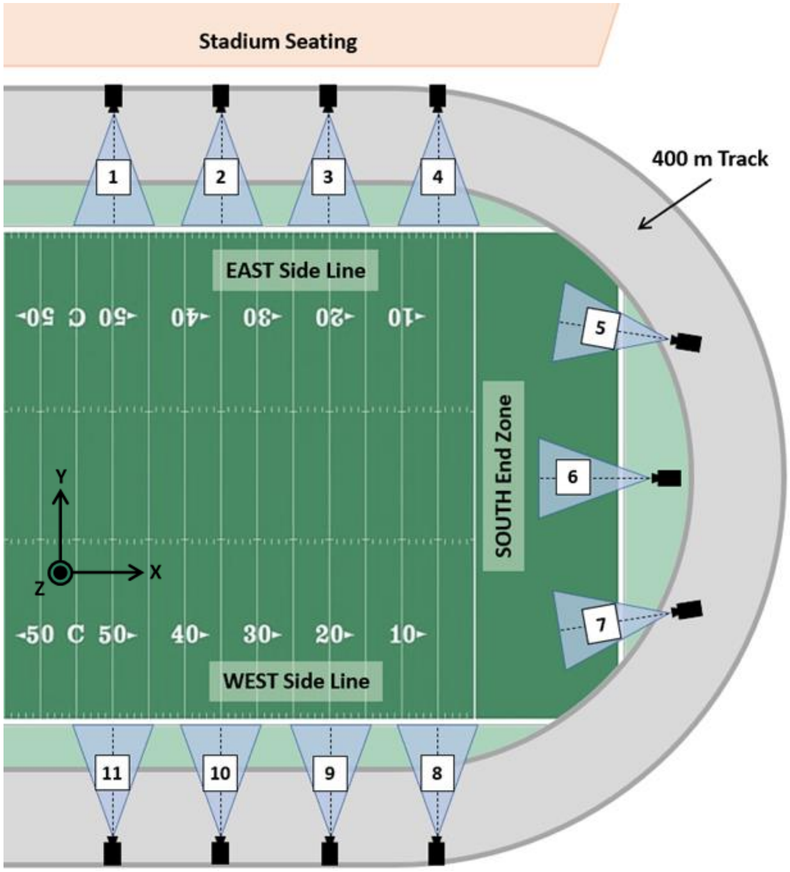

Figure 2.1 – Schematic of the general camera locations around the south half of the field (4 cameras along each side line at 15-yard intervals, 3 cameras across the back of the end zone).

Video analysis of helmet-to-ground impacts

The following is a summary of the video analysis procedures; a worked example is provided in Appendix A. Game video was reviewed and any potential impact events involving clearly observable, direct helmet contact with the ground were identified; no restrictions were placed on injurious or non-injurious impacts. Head injuries were defined based on inspection of the game video for any evidence of injury (e.g., visible signs of neurologic impairment or displays of injury behavior) immediately following impact and whether any stoppage of play or on-field medical intervention was required. Impacts were selected for video analysis based on the quality of camera views available in relation to the field location where the impact occurred. Factors such as the degree of view obstruction of the helmet, camera angle separation and camera distance were considered when assessing video quality (Appendix B). A minimum of two separate 41° FOV camera views of the helmet impact that provided approximately 150 ms (18 frames) of video data pre- and post-contact with the ground were required for 3D video tracking. A subset of 21 impact cases met the criteria for video analysis from a total of 57 cases observed in the game video, wherein ground contact was identified as the primary helmet impact mechanism. For these impacts, the video was analyzed frame-by-frame to synchronize camera views using a discrete event (e.g., moment of helmet contact with ground, hand or heel striking the ground, etc.). Three-second video clips and the associated image sequences for each camera view were then extracted to analyze the helmet kinematics.

Descriptive parameters related to each H2G impact case were documented from the video clips. This included game situation factors such as play type, player position, game time and approximate field location. Mechanisms of the H2G impact, such as the helmet impact location, impact activity and the precipitating contact type(s) leading to H2G impact (e.g., body-to-body (B2B), body-to-ground (B2G), helmet-to-body (H2B), helmet-to-helmet (H2H)), were also recorded. Standardized terminology and definitions used for the descriptive parameters were based on aspects of previous work that characterized sport-related head impacts (Jadischke et al., 2020; Kent, Forman, Bailey, Funk, et al., 2020; Lessley et al., 2018).

Quantitative video analysis of the helmet kinematics was conducted using 3D motion analysis software (ProAnalyst 3D; Xcitex Inc., Woburn, MA, USA). Calibration images and video image sequences from the two most optimal camera views of the impact were imported into the software. Camera positions relative to the football field were computed using shared reference points between calibration images based on field markings of known dimensions (e.g., yard lines, side lines, hash marks) and free-standing calibration objects temporarily placed at predetermined locations on the field to provide references in the vertical plane. The 3D field coordinate system was then superimposed onto the respective image sequences (*x*-axis: parallel to side lines; *y*-axis: parallel to yard lines; *z*-axis: orthogonal to the field surface) such that the origin of three orthogonal axes were set in close proximity to the site of impact. Two-dimensional (2D) helmet positions were tracked in both camera views by manually selecting the center of the helmet in each frame pre- and post-impact with the ground (Figure 2.2). The 2D helmet tracks were then merged (using the 3D field coordinate system) to resolve the 3D helmet positions throughout the impact event. Uncertainty error associated with the estimated 3D position coordinates was reported to assess the accuracy of the video tracking, which was

t = -0.058 s

t = 0.000 s

t = 0.058 s

Figure 2.2 – Example of a 2D helmet track using the motion analysis software for a single-camera view along the side line. The series of images shows the frame of helmet-to-ground (H2G) impact (t = 0.000 s) and the frames ± 0.058 s pre- and post-impact. Appendix A provides further detail of the video analysis procedures used to quantify the 3D helmet motion for this example, such as additional pre-impact frames and the 2D track corresponding to a second camera view.

quantified as the midpoint of the shortest distance between the epipolar lines in each camera view for each point tracked, based on the 3D calibration established for that trace.

All 3D positional data derived from the video tracking were filtered using a dual-pass, fourth-order Butterworth filter with a 15 Hz cut-off frequency, as determined by residual analysis (Winter, 2009), and differentiated using the central difference method to calculate translational velocity. Parameters extracted from the velocity data to define helmet kinematics included resultant, horizontal (i.e., ground plane) and vertical pre-impact translational velocity (V_0) and change in translational velocity due to impact (ΔV). Frame-by-frame video inspection was used to define Δt: the time interval between the start (t_0) and end (t_f) of helmet contact with ground. The resultant ΔV was determined by first using vector subtraction to calculate the difference in velocity along each axis of the field coordinate system from V_0 (one frame prior to t_0) and the end of helmet contact with the ground (t_f), and then taking the sum of squares. Helmet impact angle relative to the field (α) was also calculated. Table 2.1 provides a list of all kinematic parameters used to analyze the impact cases and their definitions.

Statistical analysis

Independent samples t-tests were used to compare mean differences across all kinematic parameters between age divisions (9–12 years vs. 13–14 years) and helmet impact location (rear vs. side). Mann-Whitney U tests were run if the assumptions of the parametric tests were violated. All statistical tests were executed using SPSS 25 (IBM SPSS Statistics, IBM Corporation, Somers, NY, USA).

Table 2.1 – Definitions of kinematic parameters used to analyze helmet-to-ground impacts.

Symbol	Definition	Equation
$(V_0)_{xy}$	Pre-impact horizontal translational velocity one frame (8.33 ms) prior to helmet contact with ground (t_0)	$= \sqrt{(V_0)_x{}^2 + (V_0)_y{}^2}$
$(V_0)_z$	Pre-impact vertical translational velocity one frame (8.33 ms) prior to helmet contact with ground (t_0)	
$(V_0)_R$	Pre-impact resultant translational velocity one frame (8.33 ms) prior to helmet contact with ground (t_0)	$= \sqrt{(V_0)_x{}^2 + (V_0)_y{}^2 + (V_0)_z{}^2}$
t_0	Time of start of helmet contact with ground, as determined from video inspection	
t_f	Time of end of helmet contact with ground, or time when ground contact is no longer affecting helmet impact kinematics (Kent, Forman, Bailey, Funk, et al., 2020), as determined from video inspection	
Δt	Time interval of helmet contact with ground	$= t_f - t_0$
ΔV_{xy}	Impact-induced change in horizontal translational velocity from V_0 to t_f	$= \sqrt{\Delta V_x{}^2 + \Delta V_y{}^2}$
ΔV_z	Impact-induced change in vertical translational velocity from V_0 to t_f	
ΔV_R	Impact-induced change in resultant translational velocity from V_0 to t_f	$= \sqrt{\Delta V_x{}^2 + \Delta V_y{}^2 + \Delta V_z{}^2}$
α	Angle of $(V_0)_R$ relative to the field (ground plane)	$= \tan^{-1}\left[\frac{(V_0)_{xy}}{(V_0)_z}\right]$

Results

A total of 21 H2G impact cases (9–12 year age division, *n* = 9; 13–14 year age division, *n* = 12) were evaluated using 3D video analysis; all cases were deemed non-injurious, as previously defined. The average maximum error for the 3D calibrations was 2.1 ± 0.4 cm and the average maximum uncertainty (±) error associated with the calculation of the 3D position coordinates from the helmet tracking was 1.5 ± 0.3 cm (Table 2.2).

Table 2.2 – Error values of the 3D calibration and helmet tracking across all helmet-to-ground impact cases.

	Calibration Error (cm)			Uncertainty ± Error (cm)		
	Mean Error	Min. Error	Max. Error	Mean Error	Min. Error	Max. Error
Mean	1.2	0.4	2.1	0.7	0.0	1.5
Range	0.8–1.7	0.0–1.1	1.4–2.7	0.3–1.1	0.0–0.1	0.7–2.0
S.D.	0.3	0.3	0.4	0.2	0.0	0.3

Mechanisms of helmet-to-ground impacts

Helmet impact with the ground occurred at either the second or third contact of the impact event, following a B2G-H2G (n = 4) or B2B-B2G-H2G progression (n = 17); four cases involved incidental helmet contact after the H2G impact. Whole-body kinematics of the H2G impacts varied across the cases, but most often reflected the general "whipping" characteristics recently described by Kent, Forman, Bailey, Funk, et al. (2020) (see Appendix C for narrative descriptions of the impact conditions involved with each H2G impact case). For the 9–12 year age division, all impact cases occurred during rush plays, while the 13–14 year age division cases included both rush and pass scenarios. Offensive players (particularly the quarterback, n = 4) represented a higher number of the impact cases overall than defensive players. The distribution of helmet impact locations was led by rear (n = 11) impacts to the helmet shell, followed by side (n = 7) and front (n = 3) impacts, respectively. A summary of the general descriptive parameters is found in Table 2.3.

Table 2.3 – Summary of descriptive parameters for all helmet-to-ground impact cases.

	Player		Play Type		Helmet Impact Location		
Age Division	Offense	Defense	Rush	Pass	Rear	Side	Front
9–12 years old	5	4	9	0	4	2	3
13–14 years old	7	5	5	7	7	5	0
Overall	12	9	14	7	11	7	3

Note. H2G impact for 6 of the 7 pass plays involved the quarterback being tackled or knocked down; of these cases, 4 resulted in H2G impact for the quarterback and 2 resulted in H2G impact for the defensive player.

Note. A total of 5 impact events (10 cases) occurred in which a successful tackle resulted in both the offensive and defensive player experiencing a significant H2G impact on the same play; this includes cases in which the quarterback was able to throw away the ball prior to being tackled to the ground.

Helmet-to-ground impact kinematics

Table 2.4 presents the kinematic results of the 3D video analysis for the 21 H2G impact cases. Figure 2.3 depicts the average (±1 SD) translational velocity time-histories in the field coordinate system across all cases. Overall, $(V_0)_R$ ranged from 1.94 to 6.69 m/s (mean: 4.04 m/s) at an angle (α) of -49.6 ± 11.3° to the field (i.e., ground plane). $(V_0)_{xy}$ and downward $(V_0)_z$ ranged from 0.89 to 5.59 m/s and 1.27 to 3.99 m/s, respectively. No significant differences were observed for V_0 between age divisions or helmet impact location in any direction ($p > 0.05$). The average ΔV_R was 3.32 ± 1.14 m/s (range: 1.80–6.23 m/s) with most cases (17 of 21 cases, 81%) having ΔV_z values below 4.00 m/s. ΔV did not significantly differ between age divisions or helmet impact location in any direction ($p > 0.05$). On average, Δt showed that the helmet was in contact with the ground for 56 ± 20 ms during impact.

Table 2.4 – Results of video analysis (3D field coordinate system) for all helmet-to-ground impacts: 9–12 years old (*n* = 9) and 13–14 years old (*n* = 12).

		Pre-Impact Velocity (m/s)			Change in Velocity (m/s)			Time Interval (s)	Impact Location
	Case	$(V_0)_{xy}$	$(V_0)_z$	$(V_0)_R$	ΔV_{xy}	ΔV_z	ΔV_R	Δt	
9–12 year olds	1	2.32	-2.29	3.25	1.37	3.34	3.61	0.042	Rear
	2	1.87	-2.34	2.99	0.78	2.42	2.54	0.058	Front
	3	2.74	-2.77	3.90	1.25	3.47	3.68	0.083	Front
	4	0.89	-3.05	3.18	0.90	2.58	2.74	0.017	Rear
	5	3.76	-3.87	5.39	2.83	5.23	5.94	0.033	Rear
	6	2.40	-1.86	3.04	0.98	2.28	2.48	0.083	Side
	7	4.18	-2.28	4.77	0.83	3.04	3.15	0.042	Rear
	8	2.36	-1.71	2.92	0.98	1.88	2.12	0.083	Front
	9	2.52	-1.96	3.19	0.42	2.53	2.57	0.058	Side
	Mean	*2.56*	*-2.46*	*3.63*	*1.15*	*2.97*	*3.20*	*0.056*	
	Median	*2.40*	*-2.29*	*3.19*	*0.98*	*2.58*	*2.74*	*0.058*	
	Min.	*0.89*	*-1.71*	*2.92*	*0.42*	*1.88*	*2.12*	*0.017*	
	Max.	*4.18*	*-3.87*	*5.39*	*2.83*	*5.23*	*5.94*	*0.083*	
	S.D.	*0.97*	*0.68*	*0.89*	*0.69*	*0.99*	*1.15*	*0.024*	
13–14 year olds	10	2.18	-2.49	3.31	1.03	3.16	3.32	0.058	Rear
	11	4.71	-1.52	4.95	0.49	2.76	2.80	0.075	Rear
	12	2.88	-2.06	3.54	0.79	2.61	2.73	0.042	Side
	13	3.47	-1.48	3.77	0.17	1.79	1.80	0.042	Side
	14	3.38	-3.02	4.54	1.31	4.11	4.31	0.075	Side
	15	5.59	-3.68	6.69	0.99	4.08	4.20	0.033	Side
	16	3.41	-3.17	4.65	1.23	3.58	3.78	0.067	Rear
	17	4.89	-3.99	6.31	3.15	5.38	6.23	0.033	Rear
	18	2.87	-2.88	4.06	1.38	2.92	3.23	0.042	Rear
	19	1.94	-2.00	2.79	0.90	2.84	2.98	0.058	Rear
	20	4.69	-3.01	5.57	1.37	3.30	3.58	0.058	Side
	21	1.46	-1.27	1.94	0.90	1.76	1.98	0.083	Rear
	Mean	*3.46*	*-2.55*	*4.34*	*1.14*	*3.19*	*3.41*	*0.056*	
	Median	*3.40*	*-2.68*	*4.30*	*1.01*	*3.04*	*3.28*	*0.058*	
	Min.	*1.46*	*-1.27*	*1.94*	*0.17*	*1.76*	*1.80*	*0.033*	
	Max.	*5.59*	*-3.99*	*6.69*	*3.15*	*5.38*	*6.23*	*0.083*	
	S.D.	*1.29*	*0.89*	*1.41*	*0.73*	*1.01*	*1.18*	*0.017*	
Overall	*Mean*	*3.07*	*-2.51*	*4.04*	*1.14*	*3.10*	*3.32*	*0.056*	
	Median	*2.87*	*-2.34*	*3.77*	*0.98*	*2.92*	*3.15*	*0.058*	
	Min.	*0.89*	*-1.27*	*1.94*	*0.17*	*1.76*	*1.80*	*0.017*	
	Max.	*5.59*	*-3.99*	*6.69*	*3.15*	*5.38*	*6.23*	*0.083*	
	S.D.	*1.22*	*0.79*	*1.24*	*0.69*	*0.98*	*1.14*	*0.020*	

Note. Case 4, 18, 19 and 20 involved incidental helmet contact after primary H2G contact. Refer to Appendix C for a detailed description

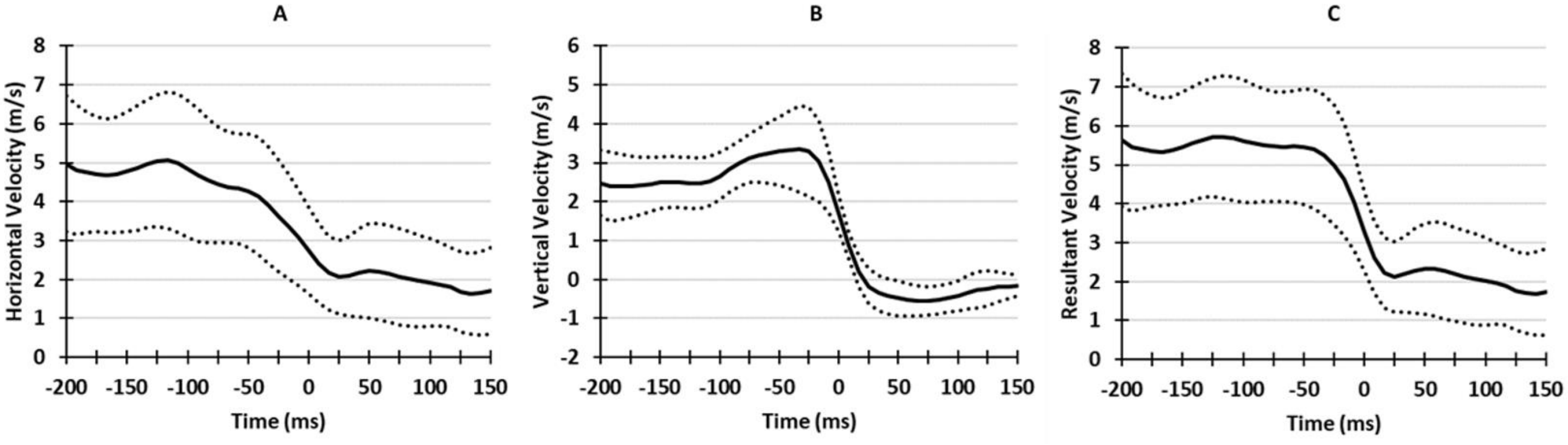

Figure 2.3 – Average (±1 SD) translational horizontal (A), vertical (B), and resultant (C) helmet velocities across all H2G impact cases. The vertical velocity direction has been modified (downward, +); negative values for translational vertical velocity indicate helmet rebound off the ground.

Based on frame-by-frame video inspection, it was determined that 15 of the 21 H2G impacts involved helmet rebound off the turf, four had no rebound (i.e., they slid on the turf or experienced incidental helmet contact after primary ground impact) and two were inconclusive (i.e., no clear frame indicating whether the helmet left the turf after impact). A secondary numerical method utilizing vertical helmet position and velocity data was assessed (Appendix D) to verify Δt and ΔV measures determined from the video. No significant differences were found between the two methods ($p > 0.05$).

Discussion

The present work illustrates that 3D motion tracking software can be an effective method to quantify in-game translational helmet velocities and severity (ΔV) of H2G impacts in youth football (≤ 14 years). All cases analyzed were significant H2G impacts that did not result in head injury. The majority of cases involved the rear or side of the helmet striking the ground, typically on the third contact of the impact progression. Initial pre-impact velocity of the helmet just prior to contacting the ground averaged 4.04 m/s, with an average ΔV_R of 3.32 m/s. The average duration of a H2G impact was approximately 0.06 s. To the authors' knowledge, the 3D helmet kinematic data reported here are a novel contribution to the understanding of the nature of helmet impacts in youth football.

While it is important to recognize that each case exhibited its own set of distinct H2G impact conditions, general patterns did emerge. Descriptive video analysis found that the youth football H2G impact cases followed either a B2G-H2G or B2B-B2G-H2G sequence, similar to previous work (Jadischke et al., 2020). All but one H2G impact from pass plays were the result of the quarterback being tackled or knocked down (29%

of total cases). Although this is likely representative of the change in skill level as the game transitions to more technical game play from youth to high school, this parallels the findings from concussive H2G impacts in the NFL (Lessley et al., 2018). Just over half of the cases involved the rear of the helmet striking the ground. The significance of this location for H2G impacts at the youth-level follows what has been reported in the NFL for significant and concussive H2G impacts (Lessley et al., 2018). The whole-body "whipping" motion observed for H2G concussions in professional football (Kent, Forman, Bailey, Funk, et al., 2020) was also seen as a predominant impact condition in these youth cases, suggesting that some similarities may exist between these two populations regarding the kinematics of H2G impacts, despite age and skill differences.

Evaluation of the pre-impact phase of the 21 non-injurious, youth football H2G impacts in this study revealed that the helmet $(V_0)_R$ averaged 4.04 ± 1.24 m/s. This magnitude was lower than the average closing velocity recently reported for 16 concussive H2G impacts in the NFL (8.3 ± 1.9 m/s) (Bailey et al., 2020; Kent, Forman, Bailey, Funk, et al., 2020). Past work by Pellman et al. (2003) reported average closing velocities of 6.0, 6.3 and 8.1 m/s for NFL H2G impact cases resulting in injury, and 3.1 m/s for the only no-injury case. Interestingly, average pre-impact velocities associated with eight un-helmeted, non-injurious H2G impacts in American 7v7 non-tackle football (5.9 ± 2.2 m/s) (Jadischke et al. 2020) were more similar in magnitude to the non-injury cases reported here. Compared to the relative velocities estimated by Campolettano et al. (2018) for H2H impacts in youth football players (range: 0.5–5.5 m/s), pre-impact velocities for the following youth H2G impacts were generally higher (range: 1.94–6.69 m/s). However, only a single-camera system was used by Campolettano et al. (2018) to establish their helmet velocities, whereas the current study utilized a multi-camera approach. Despite these findings, it is important to highlight that pre-impact velocity is not representative of impact severity since it does not consider change in velocity (ΔV) as a result of the head impacting, and potentially rebounding off, the ground.

The average ΔV_R across the youth H2G impacts was 3.32 ± 1.14 m/s. Like the pre-impact velocities, the impact severity of these non-injurious H2G impacts in helmeted youth football players was comparable to the un-helmeted, non-injurious H2G contacts in American 7v7 non-tackle football (3.0 ± 1.1 m/s) (Jadischke et al., 2020). Both were significantly less severe than the helmeted, injurious (i.e., concussive) H2G impacts experienced by professional football players: Bailey et al. (2020) and Kent, Forman, Bailey, Funk, et al. (2020) reported an average ΔV of 8.1 ± 1.7 m/s (measured via video analysis); Pellman et al. (2003) reported peak ΔVs ≥ 8.0 m/s for three injurious H2G impact cases (measured via anthropometric test dummy (ATD) laboratory reconstructions). It also is noteworthy that the one non-injurious H2G impact assessed by Pellman et al. (2003) had a much lower peak ΔV of 2.9 m/s, which is analogous to the non-injury cases in the present study. The average duration of helmet contact with the ground (Δt) for the youth H2G impacts was 56 ms, which was longer than the general range of 15 to 30 ms reported by Kent, Forman, Bailey, Funk, et al. (2020) for concussive H2G impacts in the NFL. The longer Δt values observed in this study could partially stem from the different frame rates utilized for data collection, as Kent, Forman, Bailey, Funk, et al. (2020) primarily combined camera views of lower frame rates (60 fps) with higher frame rates ranging from 180 to 540 fps. Additionally, the lower pre-impact velocities in the youth game compared to NFL athletes could also result in a longer duration of helmet contact with the ground.

The newly proposed NOCSAE standard for youth football helmets instructs that drop tests be conducted at impact velocities ranging from 3.46 to 5.46 m/s (NOCSAE, 2020). Due to rebound, these drop tests can result in ΔVs of the headform that exceed 8.0 m/s. The present study indicates that youth heads typically undergo ΔVs of, on average, 3.32 ± 1.14 m/s. This is further supported by the study from Cobb et al. (2013) which indicates that helmet impacts for 9 to 12 year old football players above the reported 95th percentile linear acceleration magnitude (43 g) result in ΔVs of only 3.8 m/s (110 g), 3.4 m/s (90 g) and 2.6 m/s (70 g), respectively (Appendix E). These studies highlight the disparity between the severity of on-field data for head impacts in the youth game and the proposed NOCSAE youth standard drop test conditions. Additionally, this study illustrates that a significant horizontal component of velocity exists during pre-impact H2G kinematics, reflecting the findings of previous NFL work (Kent, Forman, Bailey, Funk, et al., 2020). Torso inertia, surface compliance and surface friction are therefore important factors when determining impact severity and should be carefully examined in laboratory testing. The ΔV of the head can also be further influenced by the impact conditions preceding head contact with the ground (e.g., preimpact rotational motion linked to the "whipping" kinematic). Laboratory test data (Jadischke, 2017; Kent, Forman, Bailey, Cormier, et al., 2020) has demonstrated that significant forces can be transferred through the neck, especially when impacting a compliant frictional surface (i.e., artificial turf). Consequently, the neck may play an important role in H2G impacts. If the above factors are considered, these data may help inform standards committees when developing assessment methods that are more representative of real-world H2G impacts at the youth level.

This study is not without its limitations. The 3D tracking procedures and motion analysis software used only permitted the acquisition of translational helmet velocities. Moving forward, to include measures of rotational velocity in the dataset, alternative methods (e.g., MBIM, as per Jadischke et al. (2020)) should be considered, where possible. Although the general methodology and camera setup for this particular videogrammetry approach has been internally validated and used previously (Jadischke et al., 2020), the error in velocity was not directly assessed for the video analysis procedures applied in the present study. Therefore, it is important to note that additional validation of this approach is currently ongoing to evaluate the effects of specific factors that may influence the accuracy of tracking helmet motion via video, such as impact speed, camera distance, and angle. The videogrammetric technique developed and validated by Bailey et al. (2018) to analyze 3D football helmet kinematics showed that pre-impact translational velocities could be accurately estimated with an absolute error of < 0.4 m/s in low frame rate scenarios (i.e., two camera views of 60 images/s – deinterlaced video) when compared to 3D motion capture; however, at least one camera capturing at 240 images/s was required to adequately measure the rapid velocity changes associated with ΔV. Video in this study was recorded at 120 fps (progressive scan) using cameras that were stationary with fixed lenses, which virtually eliminates distortion and cumulative uncertainty that occurs due to panning and zooming lenses used in broadcast footage (Bailey et al., 2020; Kent, Forman, Bailey, Funk, et al., 2020; Newman et al., 1999; Pellman et al., 2003).

All cases analyzed in this study were non-injurious H2G impacts and, as a result, the findings are limited in their generalizability to different impact types (e.g., H2H) and those resulting in head injury, such as concussion. Moreover, since relative motion between the helmet and head is known to occur in football impacts (Joodaki et al., 2019), the 3D helmet motion tracked from the video may not fully represent the kinematics of the head. This is particularly important if trying to directly assess head accelerations, which is why the present study has focused on ΔVs. This study was also limited to three youth football games with camera views covering only half the field of play. Therefore, it is acknowledged that there may be bias related to the impacts selected for analysis since random game selection was not possible. However, this is not uncommon given the strict criteria required for 3D video analysis of in-game head impacts (Bailey et al., 2020; Kent, Forman, Bailey, Funk, et al., 2020; Pellman et al., 2003). In addition, the H2G impacts cases for youth players aligned with trends of concussive H2G impacts in professional football, in that, an over-representation of skill positions (e.g., quarterbacks) was observed (Lessley et al., 2018).

Lastly, the collection of acceleration data via ATD laboratory reconstructions of the impact cases, like what has been done in professional football (Kent, Forman, Bailey, Funk, et al., 2020; Pellman et al., 2003), was beyond the scope of this study. Future studies should consider this work as it would provide valuable insight into impact biomechanics in youth football that currently does not exist. Furthermore, while this videogrammetric approach is not immune to the challenges of video collection in an outdoor environment (e.g., camera stabilization, view obstruction, weather considerations, etc.), it offers an innovative and versatile approach to assess head impact biomechanics, not only in youth football, but other untelevised sport populations where multi-camera video data are otherwise not available.

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CHAPTER 3

A DESCRIPTIVE VIDEO ANALYSIS OF HELMET IMPACT CASES IN NORTH AMERICAN YOUTH FOOTBALL PLAYERS

Introduction

Descriptive video analysis has played an important role in characterizing real-world helmet impacts in the sport of football, which has informed efforts to improve athlete safety through training and education, policy and rule changes, as well as protective equipment innovations. This type of observational research has mostly been limited to examining cases of helmet impact in National Football League (NFL) players (Clark et al., 2017; Lessley et al., 2018; Lessley et al., 2020; Pellman et al., 2003) due to the availability of network broadcast footage and other sources that provide high-quality video with multiple views of each play (e.g., All-22 game tape, NFL Films footage, etc.).

Pellman et al. (2003) reviewed game video of severe and concussive impact cases to classify the location and source of the initial helmet contact sustained by the struck player between the 1996 and 2001 NFL seasons. The majority of the viable cases for analysis were reported to involve helmet-to-helmet impact (61%), a finding that was later supported by supplementary epidemiological work using standardized reporting forms to analyze patterns of concussion over the same 6-year period (Pellman et al., 2004). On-field characteristics of concussive impact cases in NFL games were further explored in two separate descriptive video analysis studies by Clark et al. (2017) and Lessley et al. (2018) that spanned the 2010-2011 to 2013-2014 and 2015-2016 to 2016-2017 seasons, respectively. Relative to prior work (Pellman et al., 2003; Pellman et al., 2004), the main findings from each study similarly observed a marked decrease in helmet-to-helmet impacts among concussed NFL players with a general increase in the number of helmet-to-body and helmet-to-ground impacts overall. The reduction was attributed to the development and implementation of new and revised rules in the NFL over the past two decades which were intended to address concussion incidence and improve player safety by mitigating exposure to severe helmet-to-helmet impacts. A detailed characterization of position-specific circumstances linked to concussion cases from NFL game video has also been completed by Lessley et al. (2020) with the aim of highlighting helmet design considerations unique to each player position.

The use of video analysis to investigate helmet impacts in traditionally untelevised football populations (e.g., youth athletes) has been limited. Research efforts to understand the biomechanics of helmet impacts experienced by youth football players (≤ 14 years) has been largely accomplished via sensor-driven data from helmets instrumented with accelerometer arrays, wherein video data are solely used to verify sensor recordings (Cobb et al., 2013; Daniel et al., 2014; Kelley, Kane, et al., 2017; Kelley, Urban, et al., 2017; Young et al., 2014). The few studies that have utilized video as a tool (in combination with sensor data) to examine youth football helmet impacts have primarily focused on high-magnitude impacts (≥ 40*g*) and used a single-camera view, which limits the data that can be obtained (Alois et al., 2019; Campolettano et al., 2017; Le et al., 2021).

Jadischke et al. (2020) developed a novel approach for collecting high-quality video data) that used multiple stationary action cameras to analyze head and body impacts in non-tackle American 7v7 football games for youth and varsity-aged players. This approach circumvents common issues of single-camera video analysis, mimicking professional sport by providing multiple views of the field which offers advantages such as: 1) differing camera angles for more detailed characterization of impact cases; 2) a reduced likelihood of excluding cases of interest because of view obstructions (e.g., other players, referees, etc.); and 3) eliminating the concern of missing cases that occur away from the ball (e.g., downfield blocking) due to tracking play development.

This multi-camera approach was adapted in Chapter 2 to quantify helmet velocities of helmet-to-ground impact cases from video of three youth football games. The purpose of the present study was to expand on this work and to address the relative lack of youth football head impact data by performing a descriptive video analysis of the mechanisms and situational factors for all observed in-game helmet impact cases.

Methods

In-game video recording

Video of three youth football games from two age divisions (game A: 9–12 year age division; games B and C: 13–14 year age division) was recorded between November 2018 and July 2019 at the same outdoor Canadian football field. A multi-camera approach adapted from Jadischke et al. (2020) was used to capture the game video; details of this data collection have been previously described in Chapter 2. Eleven stationary action cameras (GoPro HERO6; GoPro, Inc., San Mateo, CA, USA) with 41° field of view (FOV) lenses were positioned around the south half of the field of play. Four cameras were placed along each side line at 15-yard intervals and three across the back of the end zone. The camera locations were selected to optimize the number and quality of available camera views on the targeted area of field while limiting inference with the game-day environment. Video for all three games was recorded at 2.7 K resolution and 120 frames per second (fps) with a shutter speed of 1/1920 second (s)

(Jadischke et al., 2019). For games B and C, an overall view of the field was also captured using an additional camera (4K/60 fps, 1/960 s) with a wide-angle lens (120° FOV) located near the stadium press box. Data collection procedures for this study were cleared by the Research Ethics Board of the affiliated university (REB# 19-094). Written consent was obtained from the President of Football Operations for the home team on behalf of the players, and verbal consent was obtained from the players and teams. The game video that was recorded using the multi-camera approach described in the current study occurred alongside the compulsory recordings that are always made by each team for later film study.

Video analysis procedures

The overall framework and standardized terminology used in the present study were based on aspects of past work that characterized sport-related head impacts from video analysis (Clark et al., 2017; Jadischke et al., 2020; Lessley et al., 2018). Game video was reviewed to identify all cases of helmet impact in which clearly visible contact with another helmet, the ground or body part was observed in at least one camera view. Parameters related to the game situation for each helmet impact case were initially documented, such as game and play number, time of game, play type (rush, pass, kickoff, punt, field goal/extra point) and player position (offense, defense, special teams). Yardage lines and lateral positions across the field were used to reference the approximate field location where the impact occurred. Based on this location, three-second video clips were extracted from all available camera views (41° FOV) that captured the helmet impact case for the subsequent video analysis. Additional observations of whether a player sustained a potential head injury were also recorded.

Injury cases were defined as any visible signs of neurologic impairment or injury behaviour (e.g., loss of consciousness, hands on head, etc.) immediately following a helmet impact that resulted in the stoppage of game play or on-field medical attention.

Two trained raters independently reviewed each helmet impact case using a series of predetermined descriptive parameters (Table 3.1). Open-source software (VLC media player) was used to view the video clips, which permitted frame-by-frame analysis and the capacity to freely pan, zoom and adjust playback speed. The type of contact that occurred during each case was classified sequentially as: body-to-body (B2B), body-to-ground (B2G), helmet-to-helmet (H2H), helmet-to-ground (H2G) and/or helmet-to-body (H2B). For cases involving multiple helmet contacts, the contact subjectively viewed to be the most significant in terms of impact severity, based on the available video evidence, was identified as the primary helmet contact. Impact activity described the action of a player that led to the helmet impact case (see Appendix F). Impact source referred to the resultant entity that contacted the helmet (i.e., another helmet, the ground or a body part). Detailed and generalized helmet regions were used to determine the location of each contact on the helmet. Detailed contact locations included nine regions on the helmet shell and facemask (Figure 3.1) that were based upon prior video analysis work (Lessley et al., 2018). A 5-point rating scale (5 = excellent, 4 = good, 3 = fair, 2 = poor, 1 = very poor) was used to account for rater confidence in identifying these helmet contact locations. General contact locations were also recorded by condensing the detailed contact locations into four broad helmet regions (top, front, side, rear). The results of each rater were cross-checked to assess their agreement. A third rater acted as the adjudicator to resolve any discrepancies in the data and reviewed all cases in which the average confidence scores for detailed contact locations between the raters was ≤ 3 to verify the helmet region selected. Descriptive statistics were then used to summarize the results of the video analysis as counts and percentages.

Table 3.1 – Descriptive video analysis parameters.

Parameter	Categories
Contact type	body-to body (B2B), body-to-ground (B2G), helmet-to-ground (H2G), helmet-to-helmet (H2H), helmet-to-body (H2B)
Helmet contact source	helmet, ground, shoulder, arm, torso, thigh, knee, other
Helmet impact activity	tackled, tackling (success/fail), blocked, blocking, trip/fall, diving/leaping, other
Detailed helmet contact location	top, front, facemask (upper edge), facemask (central), facemask (side edge), side (upper), side (lower), rear (upper), rear (lower)
General helmet contact location	top, front, side, rear

Note. H2H impact involves a 'striking' and a 'struck' player.
Note. For general helmet contact locations: top = top, front = front, facemask (upper edge), facemask (central); side = facemask (side edge), side (upper), side (lower); rear = rear (upper), rear (lower).

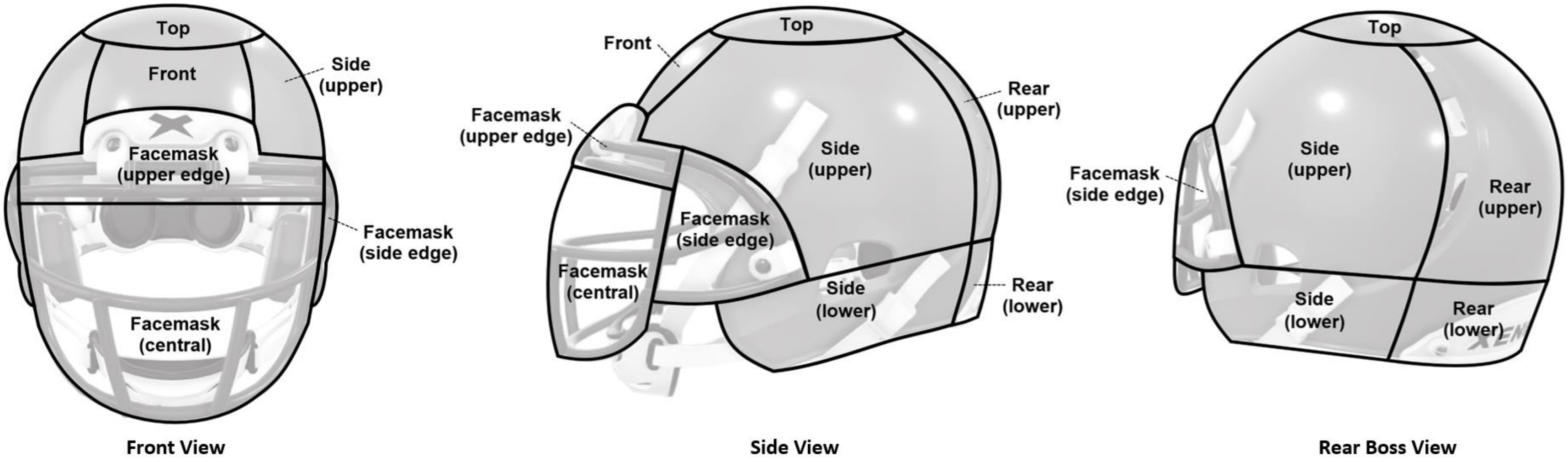

Figure 3.1 – Illustration of the detailed contact locations on the helmet shell and facemask (adapted with permission from Lessley et al., 2018).

Results

A total of 95 helmet impact cases were observed across the three youth football games (game A, *n* = 29; game B, *n* = 43; game C, *n* = 43) with 77 (81.1%) cases involving a single helmet contact and 18 (18.9%) cases involving two or more helmet contacts (Table 3.2). Only two (2.1%) helmet impact cases were associated with a potential head injury; both cases occurred in game B from a H2H contact during a failed tackling attempt. Appendix G provides a tabulated summary of the data analyzed for all cases.

Table 3.2 – Frequency (%) of helmet impact cases involving single and multiple (≥ 2) helmet contacts overall and for each game (game A: 9-12 year old division; game B and C: 13-14 year age division).

Helmet Impact Cases	Game A		Game B		Game C		Overall	
Single Contact	23	(88.5%)	28	(80.0%)	26	(76.5%)	77	(81.1%)
Multiple Contacts	3	(11.5%)	7	(20.0%)	8	(23.5%)	18	(18.9%)
Total	*26*		*35*		*34*		*95*	

Helmet contact type

For all helmet contacts identified (*n* = 115), H2G contacts were most common (*n* = 68, 59.1%), followed by H2H (*n* = 28, 24.3%) and H2B (*n* = 19, 16.5%) (Table 3.3). Helmet contact with the ground most frequently occurred as the third contact in the progression, wherein 41 (43.2%) of the 95 helmet impact cases demonstrated a B2B-B2G-H2G contact sequence.

Table 3.3 – Frequency (%) and type of helmet contact(s) (H2H: helmet-to-helmet; H2G: helmet-to-ground; H2B: helmet-to-body) overall and for each game (game A: 9-12 year old division; game B and C: 13-14 year old division).

Helmet Contact	Game A		Game B		Game C		Overall	
H2H	4	(13.8%)	12	(27.9%)	12	(27.9%)	28	(24.3%)
H2G	21	(72.4%)	23	(53.5%)	24	(55.8%)	68	(59.1%)
H2B	4	(13.8%)	8	(18.6%)	7	(16.3%)	19	(16.5%)
Total	*29*		*43*		*43*		*115*	

Game situation

All but one helmet impact case for game A occurred during a rush play (*n* = 25/26, 96.2%); greater variation in the type of play was shown for the helmet impact cases in games B and C (*n* = 69) (rush: *n* = 39, 56.5%; pass: *n* = 18, 26.1%; kickoff: *n* = 10, 14.5%; punt: *n* = 2, 2.9%). Overall, offensive (*n* = 43, 45.3%) and defensive (*n* = 39, 41.1%)) positions shared a relatively even distribution of helmet impact cases; special teams roles accounted for 13 (13.7%) cases. Grouping the approximated field locations for each helmet impact case into 20 zones on the targeted half of the field (Figure 3.2) revealed that 77 (81%) of the observed cases occurred in the mid-field, with the majority focused in the region between the center hash marks. These general field locations were consistent for both offensive and defensive player helmet impacts.

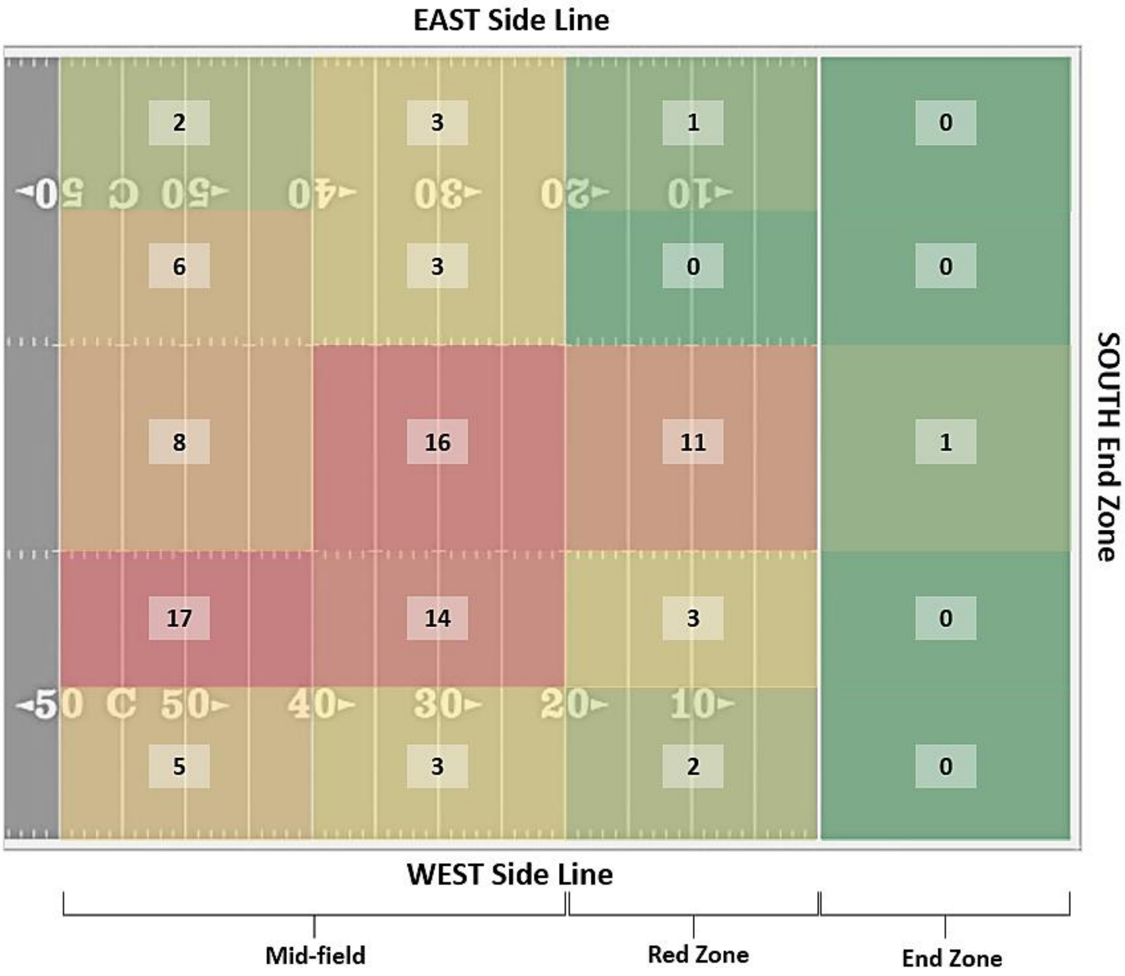

Figure 3.2 – Heat map depicting the distribution of helmet impact cases (*n* = 95) by field location.

Helmet contact location

The distribution of detailed contact locations for all helmet contacts observed (*n* = 115) showed that the rear (upper) (*n* = 33, 28.7%) and side (upper) (*n* = 32, 27.8%) regions of the helmet shell were the most frequently contacted (Figure 3.3), and were largely the result of H2G contact (Figure 3.4). Regions of the facemask and helmet shell making up the front of the helmet incurred 30.4% (*n* = 35) of all helmet contacts (front helmet shell: 9 [7.8%]; facemask (central): 16 [13.9%]; facemask (upper edge): 10 [8.7%]) from a variety of sources, collectively. Only one helmet contact (0.9%) occurred to the top of the helmet.

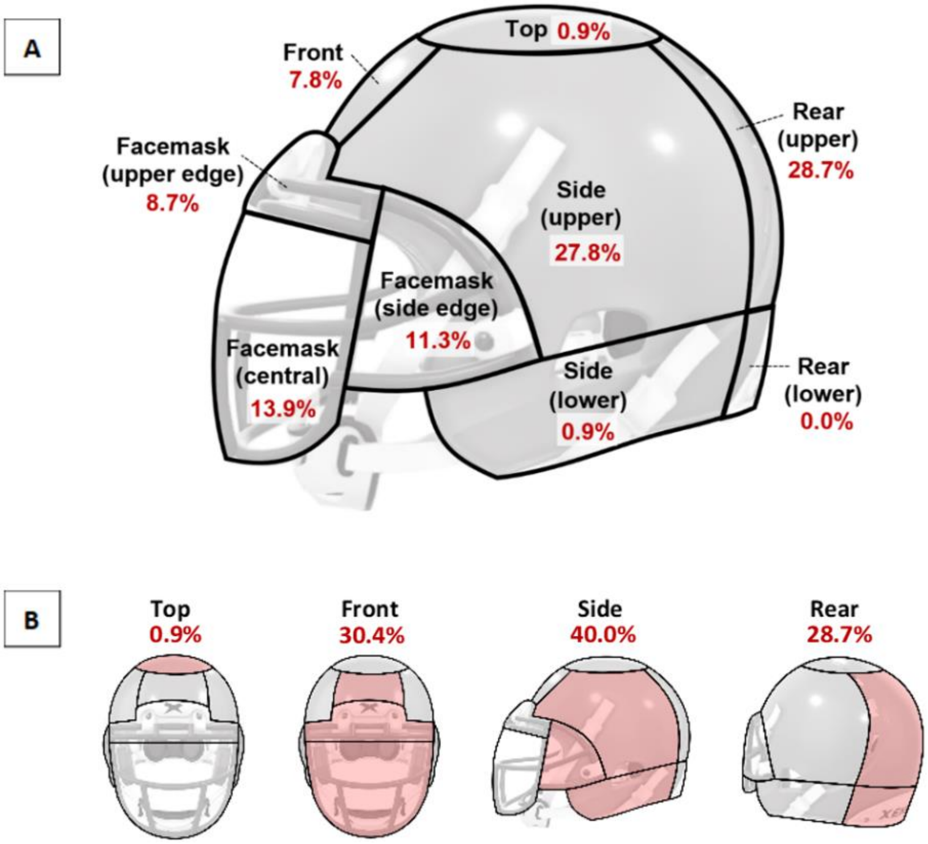

Figure 3.3 – Percentages of helmet contacts (*n* = 115) for detailed (A) and general (B) helmet contact locations on the helmet shell and facemask overall.

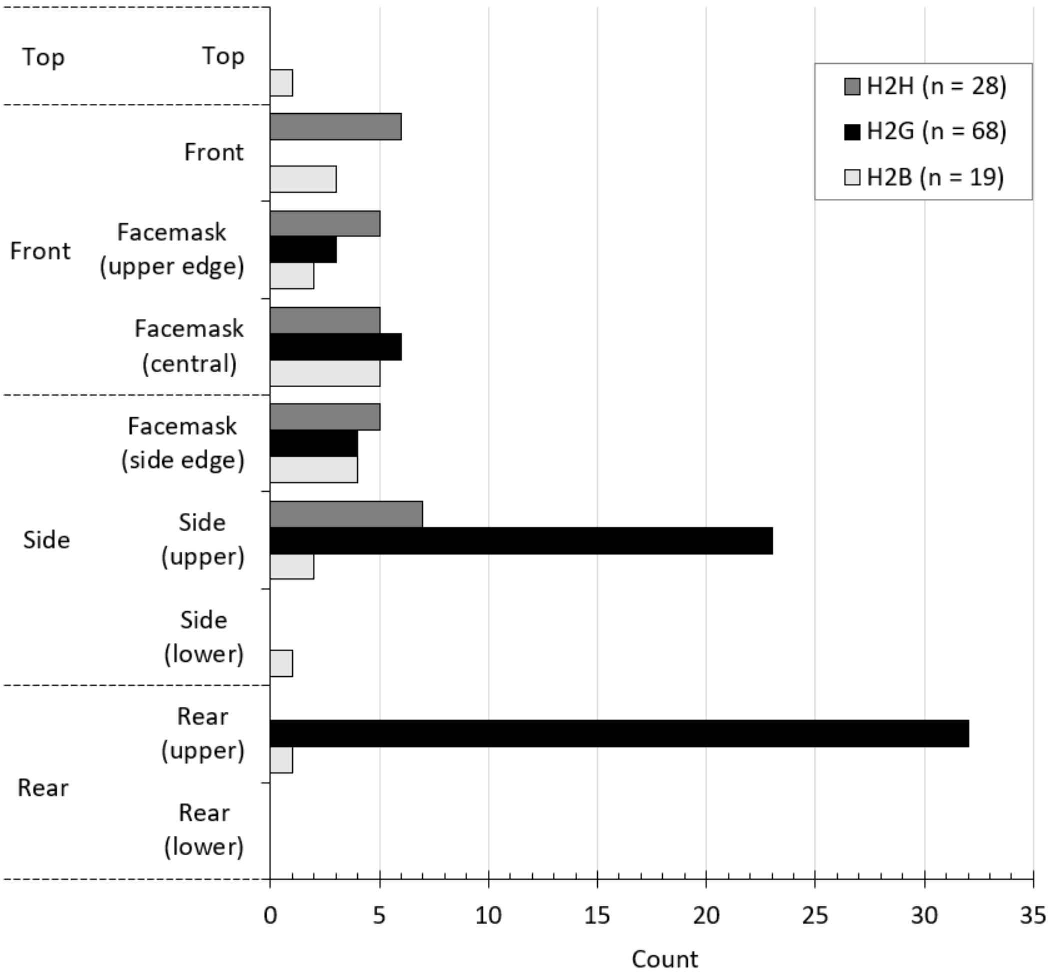

Figure 3.4 – Helmet contacts (*n* = 115) for detailed and general helmet contact locations stratified by helmet contact type (H2H: helmet-to-helmet; H2G: helmet-to-ground; H2B: helmet-to-body).

Activity leading to helmet impact

Tackling an opposing player or being tackled accounted for 39 (41.1%) and 31 (32.6%) of the 95 helmet impact cases identified, respectively, with most cases for these activities involving a primary helmet contact with the ground (Figure 3.5). The 9-12 year old players (game A, *n* = 26 cases) most frequently experienced helmet impact from being tackled (*n* = 11, 42.3%). The 13-14 year old players (game B and C, *n* = 69 cases) more commonly sustained helmet impact from the act of tackling (*n* = 30, 43.5%), in which successful tackles (*n* = 21, 30.4%) had more than double the cases than failed tackles (*n* = 9, 13.0%). For helmet impact cases categorized as 'other' (*n* = 9), all primary H2G and H2H contacts were the result of a quarterback knockdown (*n* = 6) or ball carrier running through a failed tackle (*n* = 3), respectively.

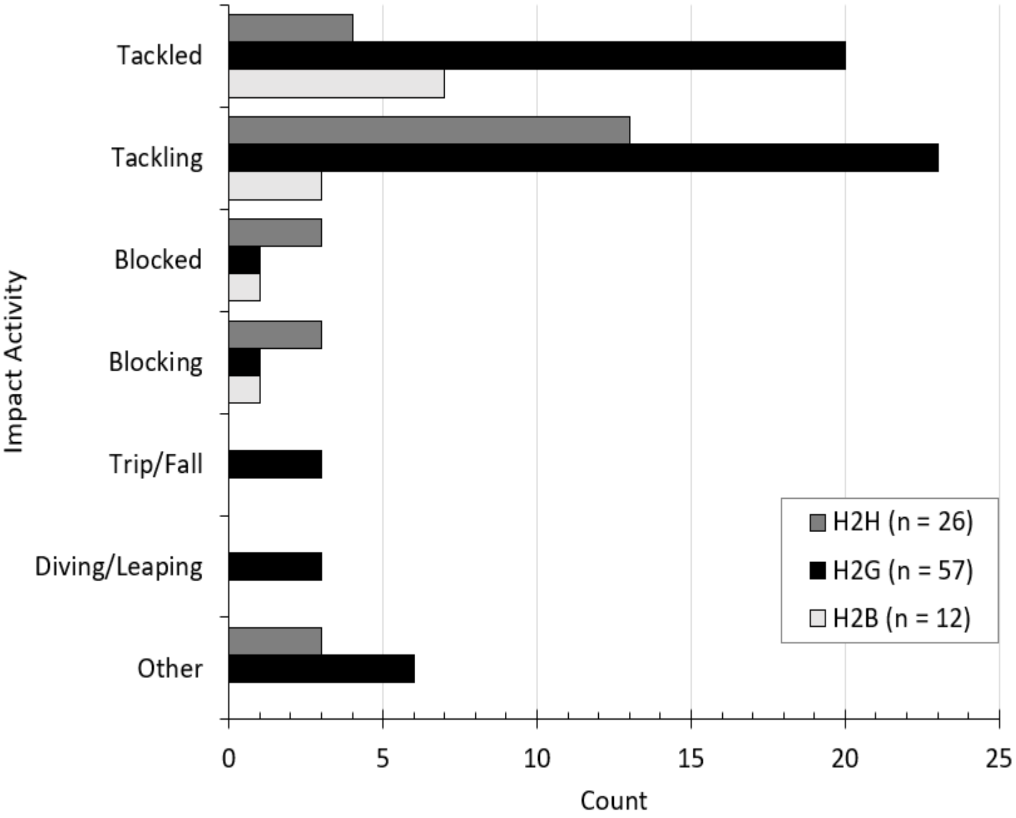

Figure 3.5 – Primary helmet contacts (*n* = 95) for impact activity stratified by helmet contact type (H2H: helmet-to-helmet; H2G: helmet-to-ground; H2B: helmet-to-body).

Discussion

This study presents a descriptive video analysis of helmet impact cases from three youth football games across two age divisions (9–14 years old). The aim of this work was to use a multi-camera approach to provide further context of the mechanisms and situational factors associated with in-game helmet impacts experienced by youth players, similar to previous studies in professional football (Clark et al., 2017; Lessley et al., 2018; Lessley et al., 2020; Pellman et al., 2003). Overall, the majority of helmet impact cases identified occurred during a rush play and were concentrated around the mid-field. The most frequent type of helmet contact was H2G, typically following a B2B and B2G contact. Helmet contact locations were predominantly distributed between the upper regions of the rear and side helmet shell across each game. Tackling or being tackled by an opposing player were the most common activities leading to helmet impact.

Prior studies that have used single-camera video analysis to describe on-field characteristics of youth football helmet impacts have found varying results. Le et al. (2021) reported that the most common source of in-game helmet impact for a team of 10- to 11-year-old youth football players wearing Triax SIM-G sensors (14*g* minimum threshold) was H2B (45.2%), followed by H2H (31.9%) and H2G (17.8%). This opposes the results reported here, which found H2G contact to be the leading type of helmet contact observed across all games (59.1%). For a sample of youth football players aged 12.6 ± 1.3 years wearing instrumented helmets (HIT System), Alois et al. (2019) determined that H2H contact accounted for 71.9% of in-game impacts; however, this study focused on high-magnitude impacts ($\geq 40g$) involving intentional use of the head, which does not align with H2G impact mechanisms. The higher proportion of H2G contacts observed in the present work could be attributed to the differences in using a video-based compared to a sensor-based approach for identifying cases of helmet impact (Kuo et al., 2018), especially since the exposure data consists of all visually observable instances of physical helmet contact that may not have met the linear acceleration thresholds of these sensor-based studies. The two helmet impact cases resulting in potential head injury in this study involved significant H2H contact, reflecting the main type of impact linked to concussion in youth football (Chrisman et al., 2019; Kontos et al., 2013).

Helmet impact cases predominantly occurred during a rush play; a typical offensive strategy at the youth level. Passing emerged as a more prominent play type for cases of helmet impact in games B and C, highlighting the progression in the level of play between age groups. The location of helmet impact cases on the field showed similar trends for both offensive and defensive players, with 81% occurring in the middle of the field outside of the red zone and end zone. Field locations reported from NFL video review of concussive impacts found that 66.7% of concussions occurred between the offensive and defensive 20-yard lines (Clark et al., 2017). However, game video in the current study only captured half the field of play and included all types of helmet impact cases (i.e., non-injury and injury). Nonetheless, based on this finding, future research using video to assess in-game youth football helmet impacts should consider including more mid-field camera views to better visualize potential cases.

To the authors’ knowledge, this is the first study to quantify the contact locations of youth football helmet impacts using a video-based approach. Previous reports of helmet contact locations for youth populations have relied on generalized estimations (i.e., top, front, side, rear) from instrumented helmets equipped with accelerometer arrays (Cobb et al., 2013; Daniel et al., 2012, 2014; Kelley, Kane, et al., 2017; Kelley, Urban, et al., 2017; Munce et al., 2015; Young et al., 2014), which can be inaccurate and require careful interpretation (Beckwith et al., 2012; Siegmund et al., 2016). Generalized contact locations from the current video analysis showed that the side of the helmet was most frequently contacted overall (40.0%). Detailed contact locations revealed that rear (upper) and side (upper) helmet regions accounted for over half of all helmet contacts observed (56.5%) and 81% of H2G contacts. This reflects the findings from Lessley et al. (2018) that concussive NFL impacts involving helmet contact with the ground were more highly represented by the upper rear and side helmet shell locations. The performance of these helmet regions for attenuating ground impact forces should therefore be considered in future youth-specific helmet designs.

A strike to the ground during the act of tackling was found to be a common mechanism of helmet impact in this study, accounting for approximately 25% of cases overall. This was largely observed in games B and C, wherein players more frequently sustained a H2G contact from a successful compared to a failed tackling attempt. Video analysis of NFL games also determined that tackling was the primary mechanism of helmet impact in professional players; however, this was specific to reported concussion events, wherein H2B impacts (i.e., no pure shoulder contact) comprised the greatest proportion (20%) (Lessley et al., 2018). Efforts to educate and train football players on safe tackling techniques have been an important strategy for reducing helmet impact exposure, with a focus on proper head positioning and use of the shoulder or chest during initial contact (i.e., head-up technique) (Heck et al., 2004). This research suggests that potential helmet interaction with the ground following the initial contact from a tackling attempt may require further investigation for youth players, especially considering the unique mechanics of H2G impacts in football (Chapter 2; Kent et al., 2020).

This study has several key strengths and also some notable limitations. Helmet impact cases identified for video analysis could be examined in greater detail without the drawbacks of single-camera setups that utilize panning and zooming lenses with lower frame rates since multiple fixed lens, stationary cameras were used that recorded video at 120 fps. However, it is important to note that the results of this study are based on only three full games of video data. Furthermore, the camera layout was constrained to half the field to ensure multiple views of any potential helmet impact case; had the games been played on an American (120 x 53 ⅓ yards) rather than a Canadian (150 x 65 yards) football field, more field coverage may have been possible. For these reasons, the generalizability of the findings is limited to the video data available for review and epidemiological measures (e.g., impact exposure rates) could not be reported.

The authors acknowledge the subjectivity of this video analysis. Unlike sensor-based studies, identification of helmet impact via video favours skill positions (i.e., "non-linemen") and open-field impacts (Pellman et al., 2003) as the line of scrimmage has less clear views due to close, multi-player action. Moreover, despite the use of multiple field-level cameras, occasional view obstructions (e.g., referee interference, etc.) were still evident. Consequently, even though helmet impacts across all player positions were considered in the video review, selection bias may have been present in the dataset; therefore, positions were limited to offensive, defensive or special teams roles. The inclusion of supplementary overhead views could help mitigate this issue in future work.

Impact severity was not measured in this study as all cases of observable helmet impact were documented, regardless of whether a head injury was present or not. However, documenting all helmet impacts, in spite of the perceived severity, could prove to be valuable at the youth level.

The multi-camera approach presented here offers a unique solution for acquiring high-quality multi-view video that can be used to characterize on-field helmet impacts in untelevised youth football populations. The results of this descriptive video analysis demonstrated the significance of H2G impacts in youth football game play, and that special attention may be warranted for the performance of the upper rear and side regions of the helmet shell against turf (i.e., ground) impact. This research also emphasized the importance of tackling as a mechanism of in-game helmet impact for youth football players, wherein safe tackling techniques should consider methods of mitigating H2G impact in addition to H2H impact. Key situational factors of helmet impact included rush plays and impact locations in the mid-field, which are both expected for this age and skill level. This study represents a promising first step to building a database of helmet impact cases experienced by youth football players consistent with previous work in the NFL (Clark et al., 2017; Lessley et al., 2018; Lessley et al., 2020; Pellman et al., 2003), such that head injury characteristics in the youth population can be better understood.

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CHAPTER 4

VALIDATION OF A MULTI-CAMERA VIDEOGRAMMETRY APPROACH FOR QUANTIFYING HELMET IMPACT VELOCITY IN FOOTBALL

Introduction

Understanding the underlying biomechanics of head impacts experienced by youth football players is a critical aspect of the continued effort to improve player safety, particularly through the development of better helmet test standards and designs. Advancements in sensor-based technology, such as instrumented helmets equipped with helmet-mounted accelerometer arrays (Duma et al., 2005; Rowson et al., 2011), have provided researchers with a method to estimate on-field head kinematics during an impact. Previous studies that have quantified head impact kinematics in youth football have relied almost exclusively on this sensor-driven data (Campolettano et al., 2017; Cobb et al., 2013; Daniel et al., 2012, 2014; Kelley, Kane, et al., 2017; Kelley, Urban, et al., 2017; Munce et al, 2015; Young et al., 2014); however, the level of accuracy of these devices for measuring head acceleration rather than helmet acceleration has been questioned (Jadischke et al., 2013; Joodaki et al., 2019; Siegmund et al., 2016) and little effort has been taken to assess the severity of these head impacts through alternative measures (i.e., change in velocity). Alternatively, video-based methodologies have also been employed to measure helmet impact kinematics in football (Chapter 2; Bailey et al., 2020; Campolettano et al., 2018; Kent et al., 2020; Pellman et al., 2003), but to a much lesser extent and with mixed levels of complexity.

To date, most research that has used video as the primary means to quantify helmet impact kinematics in football has utilized broadcast footage from National Football League (NFL) games. Pellman et al. (2003) analyzed 31 severe impacts (25 concussions, 6 no injury) from NFL game video between 1996 and 2001 using a previously developed videogrammetry technique (Newman et al., 1999; Newman et al., 2000). Parameters calculated from the video were limited to the pre-impact conditions for each case (i.e., helmet impact velocity, closing speed between two colliding players); physical reconstructions of the impact cases using anthropomorphic test devices (ATDs) were conducted to determine head kinematics during impact. Validation testing found that the estimated error of the video-derived velocities could be upwards of 11% depending on the direction of motion and distance relative to the camera (Newman et al., 2005). More recently, a detailed study by Bailey et al. (2018) assessed the accuracy of a videogrammetry technique using model-based image-matching (MBIM) that has since been applied to analyze concussion impact biomechanics in NFL games (Bailey et al., 2020; Kent et al., 2020). Factors that affect broadcast video quality were evaluated, specifically the error associated with using different combinations of low (60-60 Hz), intermediate (240-60 Hz) and high (240-240 Hz) frame rate scenarios for tracking helmet motion. It was reported that resultant translational and rotational pre-impact helmet velocities were the only kinematic parameters that maintained an acceptable level of accuracy across all frame rates, with absolute errors of less than 0.4 m/s and 0.9 rad/s, respectively.

Due to the lack of high-quality video available for populations outside of professional sport, video-based methodologies have not been a common research strategy for investigating on-field helmet impact biomechanics in youth football. One study by Campolettano et al. (2018) measured helmet-to-helmet impact velocities from video of youth football games; however, the single-camera system that was used restricted three-dimensional (3D) motion to changes in two-dimensional (2D) position on a perspective grid aligned with the field surface, limiting the accuracy of the velocity estimations. In Chapter 2, the velocities of in-game helmet-to-ground impacts experienced by youth football players were quantified using a multi-camera videogrammetry approach adapted from a study by Jadischke et al., (2020). The 3D kinematic data reported from this work offer valuable insight into our understanding of the nature of helmet impacts in youth football, and present a methodology to collect video-based data of on-field impacts that is not reliant on broadcast footage. The objective of this research was to confirm the validity of the multi-camera videogrammetry approach established in Chapter 2 for measuring helmet impact velocities in youth football and determine the effects of camera angle, camera distance and speed of impact on the accuracy of the 3D video tracking process.

Methods

Methodological details of the multi-camera videogrammetry approach used in the present study were previously described in Chapter 2. For the purpose of this validation research, a simplified version of the full-scale data collection procedure was replicated at the same outdoor Canadian football field.

Camera positioning

Eight stationary action cameras (HERO6; GoPro, Inc., San Mateo, CA, USA) with 41° field of view (FOV) lenses were set up around half the field of play: seven at field level and one overhead at the top of the stadium seating (Figure 4.1). The locations of the cameras were selected to assess the effects of camera distance and camera angle on the videogrammetry approach. Camera distance was assessed by targeting two separate zones (A and B) on the field that provided varying distances (i.e., closer to and farther away) from the respective camera views; camera angle was assessed by using different pairs of camera views (orthogonal, coincident, parallel and overhead). A brief description of the camera combinations associated with each zone can be found in the footnote of Table 4.1. All cameras recorded video at 2.7K resolution and 120 frames per second (fps) with a shutter speed of 1/1920 seconds (Jadischke et al., 2019). Calibration images from each camera view were also captured to set the 3D field coordinate system during video analysis.

Free fall drop tests

Two independent series of free fall drop tests were conducted in each zone using an apparatus that quick-released a helmeted ATD head and neck assembly such that the rear upper helmet shell impacted the turf (Figure 4.2). This approach reflects a common impact site observed for helmet-to-ground impacts across various football populations (Chapter 2; Kent et al., 2020; Lessley et al., 2018). In compliance with the laws of physics (Equation 3.1), drop heights of 1.04 m and 1.83 m were used to achieve slow (4.52 m/s) and fast (5.99 m/s) reference free fall velocities at ground impact that are within the range of helmet-to-ground impact velocities reported for youth football (1.94–6.69 m/s) (Chapter 2). After each impact trial, helmet fit was checked and adjustments were made to reset the drop test conditions when necessary. Three impact trials were analyzed for each of the reference velocities within zone A and B on the field.

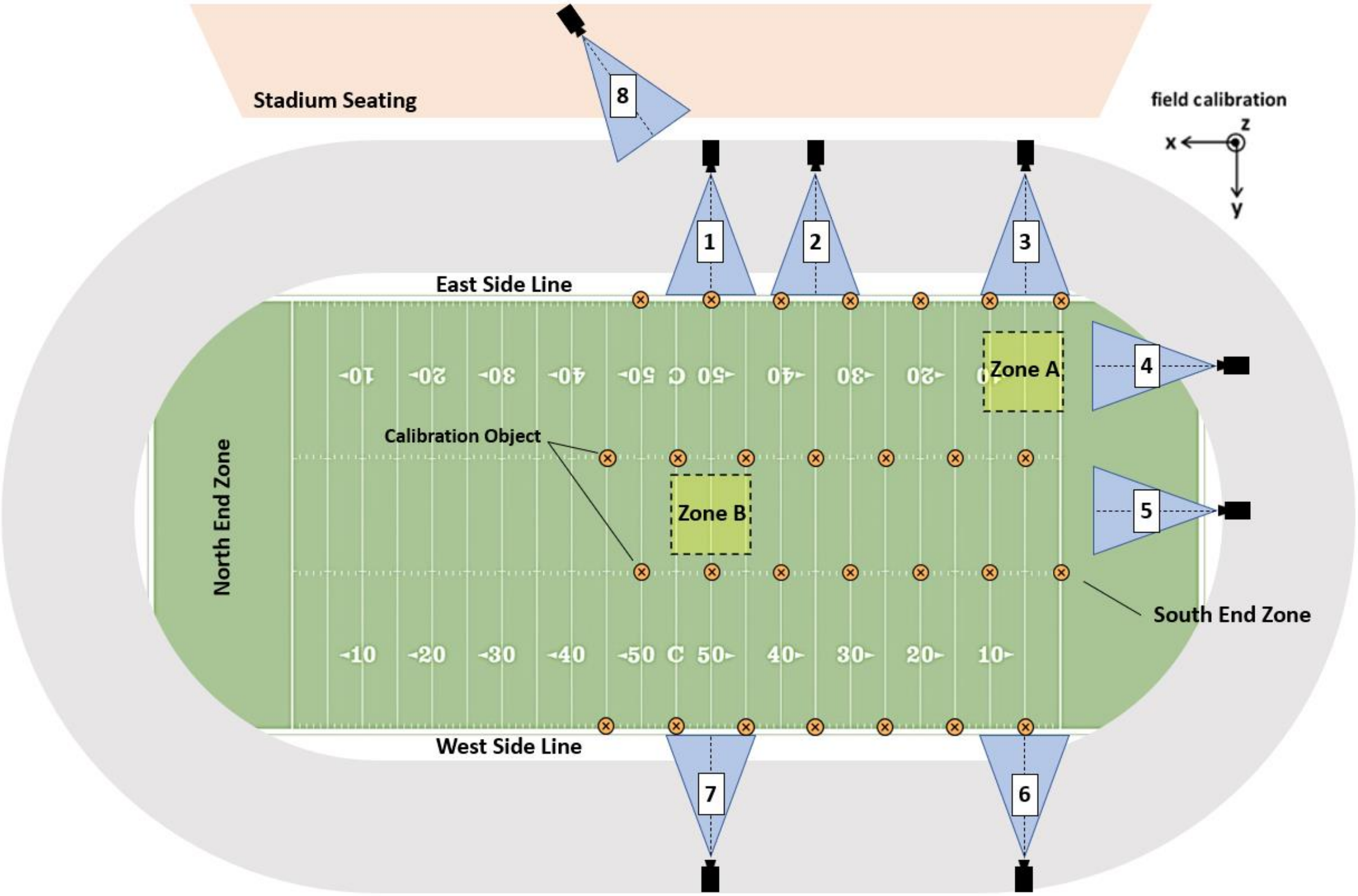

Figure 4.1 – Schematic of the eight stationary camera positions (field-level: C1-C7; overhead: C8) and field locations for the two test zones and calibration objects.

Table 4.1 – Description of camera views, uncertainty error and calibration results for videogrammetric analysis.

Zone	Camera Angle	Camera Pair		Helmet Resolution (pixels/helmet)^2		Calibration Error (cm)		Uncertainty ± Error (cm)			
								Drop Test - Slow		Drop Test - Fast	
		View 1	View 2	View 1	View 2	Mean (±SD)	Range	Mean (±SD)	Range	Mean (±SD)	Range
A	Orthogonal	C3	C4	1849	1296	0.9 (0.4)	0.5–1.6	0.2 (0.1)	0.0–0.6	0.6 (0.3)	0.1–1.0
	Coincident	-	-	-	-	-	-	-	-	-	-
	Parallel	C3	C6	1849	400	1.9 (0.8)	0.6–2.8	2.1 (1.2)	0.1–4.3	6.0 (2.6)	0.7–10.0
	Overhead 1	C3	C8	1849	529	0.9 (0.4)	0.5–1.8	1.3 (0.4)	0.5–1.9	0.5 (0.3)	0.0–1.3
	Overhead 2	C4	C8	1296	529	1.2 (0.9)	0.2–2.4	1.4 (0.4)	0.4–2.1	0.8 (0.5)	0.1–2.4
B	Orthogonal	C1	C5	784	289	1.2 (0.5)	0.4–2.1	0.7 (0.4)	0.0–1.6	0.7 (0.4)	0.1–1.5
	Coincident	C1	C2	784	729	1.5 (0.7)	0.6–2.3	1.0 (0.5)	0.1–2.0	1.1 (0.6)	0.0–2.0
	Parallel	C1	C7	784	784	1.6 (0.9)	0.0–2.8	2.1 (1.4)	0.1–5.0	6.3 (2.0)	1.0–9.6
	Overhead 1	C1	C8	784	529	5.7 (3.3)	1.0–12.6	-	-	-	-
	Overhead 2	C5	C8	289	529	1.8 (0.8)	0.2–2.9	1.2 (0.5)	0.2–1.9	1.0 (0.6)	0.1–2.0

Note. Orthogonal = side line camera view (east) and end zone camera view (south); Coincident = two adjacent camera views along the same side line (east); Parallel = two camera views on opposite side lines (east and west); Overhead 1 = side line camera view (east) and overhead camera view (stadium seating); Overhead 2 = end zone camera view (south) and overhead camera view (stadium seating).

Note. C1 = camera 1, C2 = camera 2, C3 = camera 3, etc.

Note. Overhead camera view (C8) could not capture both target zones in its field of view; therefore, it was angled toward each respective zone for video collection.

Note. Coincident camera angle was not analyzed in zone A because field location of the drop test was too close to east side line to permit side-by-side camera views 15 yards apart; calibration for the Overhead 1 camera angle in zone B was greater than 3 cm, and therefore, was not included in the video tracking.

Note. Resolution is provided in pixels per area of the helmet for each camera view (as per Bailey et al., 2018).

Figure 4.2 – Apparatus set-up for free fall drop test of helmeted anthropomorphic test device (Hybrid III 50th percentile male) head and neck assembly.

Video analysis

Video analysis of the helmet velocity was performed using 3D motion analysis software (ProAnalyst 3D; Xcitex Inc., Woburn, MA, USA). Calibration images and video image sequences for each impact trial were extracted from the camera views associated with each zone and imported into the software. For each camera angle analyzed, shared reference points between the calibration images from the two camera views were selected to compute the camera positions relative to the football field; this included field markings (e.g., yard lines, side lines, hash marks) and free-standing calibration objects of known dimensions. A 3D field coordinate system was then superimposed onto the corresponding image sequences (*x*-axis: parallel to side lines; *y*-axis: parallel to yard lines; *z*-axis: orthogonal to the field surface) such that the origin of the three orthogonal axes was set in close proximity to the drop test impact site. Video data for each impact trial were analyzed frame-by-frame in all camera views to synchronize the image sequences according to the frame of initial helmet contact with the ground. Two-dimensional helmet positions in each camera view were tracked by manually selecting the center of the helmet pre- and post-impact with the ground, wherein a mid-point finder tool (used to assist in finding the center of circular objects) was enabled. A basic image sharpening filter and adjustments to image processing features (e.g., contrast) were also applied in the software to help optimize the digitization process. Three-dimensional helmet positions were then resolved by merging the 2D helmet tracks from the pair of views for a given camera angle using the matching 3D field coordinate system. Average uncertainty error associated with the 3D position estimates (i.e., the midpoint of the shortest distance between the epipolar lines in each camera view for each point tracked, based on the 3D calibration) was reported to assess video tracking accuracy.

Data processing and analysis

Translational velocity of the helmet during the drop tests was computed by filtering the 3D positional data using a dual-pass, fourth-order Butterworth filter with a 20 Hz cut-off frequency (determined by residual analysis (Winter, 2009)), and then differentiating via the central difference method. The average impact velocity (V_0) of the three impact trials, at the time point prior to helmet contact with the ground factoring into the free fall velocity estimation, was reported for each test condition. Using the reference velocities from Equation 4.1, relative error [RE, (Equation 4.2)], absolute error [AE, (Equation 4.3)] and root-mean-square error [RMSE, (Equation 4.4)] of the measured helmet impact velocities were calculated to assess 3D video tracking accuracy for all test conditions, with the average RE and AE being reported across the three impact trials.

$$V_{impact} = \sqrt{2gh} \qquad \text{(Eq. 4.1)}$$

where:

- V_{impact} is the velocity of the helmet just prior to ground contact (m/s)
- h is the drop height above the ground (m)
- g is the acceleration due to gravity (9.81 m/s^2)

$$RE = \frac{V_{video_i} - V_{reference}}{V_{reference}} \text{ x } 100 \quad \text{(Eq. 4.2)}$$

$$AE = \left|\frac{V_{video_i} - V_{reference}}{V_{reference}}\right| \text{ x } 100 \quad \text{(Eq. 4.3)}$$

$$RMSE = \sqrt{\frac{\sum_{i=1}^{N}\left(V_{video_i} - V_{reference}\right)^2}{N}} \quad \text{(Eq. 4.4)}$$

where:

- V_{video_i} is the impact velocity measured from the video analysis of the *i*th impact trial
- $V_{reference}$ is the slow (4.52 m/s) or fast (5.99 m/s) reference impact velocity from Equation 4.1
- N is the number of impact trials analyzed per test condition

The relative reliability of the helmet impact velocity estimations in each condition was evaluated using the coefficient of variation (CV) (Equation 4.5). Further statistical analysis was precluded by the small sample size for each series of drop tests ($n = 3$).

$$CV = \frac{\sigma}{\mu} \text{ x } 100 \quad \text{(Eq. 4.5)}$$

where:

- σ is the standard deviation of the impact velocities measured from the video analysis of the three repeated impact trials
- μ is the mean of the impact velocities measured from the video analysis of the three repeated impact trials

In addition to reporting the error for helmet impact velocity (V_0), the average RMSE associated with helmet velocity time-histories over a window of 150 ms pre-impact from V_0 was also calculated across the three impact trials for each test condition (Equation 4.6). A velocity-time curve of a free-falling object with an initial velocity of 0 m/s was used as the reference (Figure 4.3; Equation 4.7) with the time interval of the curve set to match the video settings (120 fps = 0.00833 s). Horizontal velocity traces were compared to a constant reference velocity of 0 m/s since, in theory, no ground plane motion should occur during the free fall. Vertical (and resultant) velocity traces were synchronized with the reference velocity-time curve such that the time point of the V_0 derived from the video analysis was aligned with the time point before the reference free fall velocity surpassed 4.52 m/s and 5.99 m/s, respectively.

$$RMSE = \sqrt{\frac{\sum_{i=1}^{N}\left(V_{video_i} - V_{reference_i}\right)^2}{N}} \qquad \text{(Eq. 4.6)}$$

where:

- V_{video_i} is the *i*th data point of the pre-impact helmet velocity measured from the video analysis
- $V_{freefall_i}$ is the *i*th data point of the reference velocity-time curve
- *N* is the number of data points analyzed over the time trace

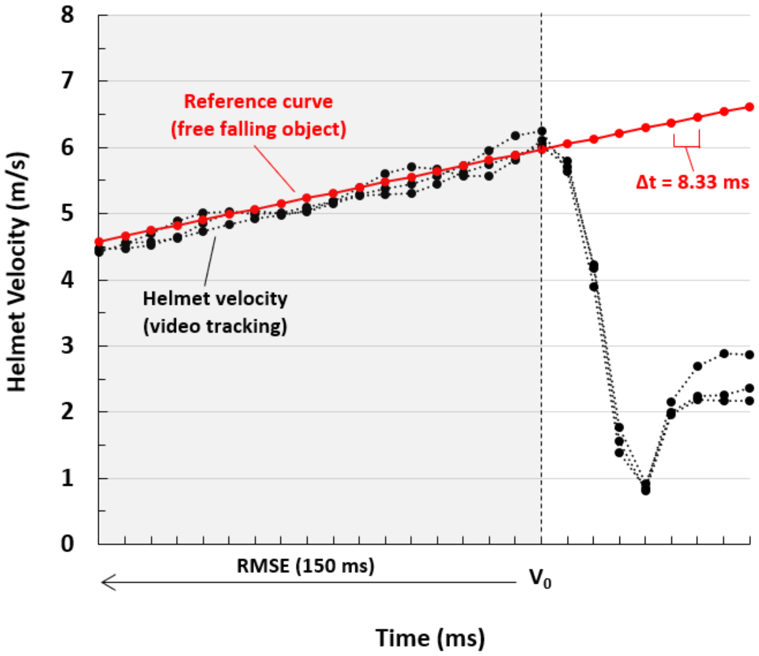

Figure 4.3 – Graphical depiction of the reference curve for a free-falling object with an initial velocity of 0 m/s used to calculate the average root-mean-square error (RMSE) for helmet velocity time-histories over a window of 150 ms pre-impact from V_0; resultant helmet velocities shown are from the fast impact trials for the orthogonal camera angle within zone A.

$$V_i = V_{i-1} + g\,\Delta t \qquad \text{(Eq. 4.7)}$$

where:

- V_{i-1} is the calculated velocity from the previous time point
- g is the acceleration due to gravity (9.81 m/s^2)
- Δt is the time interval of the recorded video (0.00833 s)

Results

Calibration error associated with setting the 3D field coordinate systems for each camera angle and the uncertainty (±) error of the 3D position coordinates from the helmet video tracking are located in Table 4.1. In general, the average maximum errors for the 3D calibrations were < 3 cm, with the exception of overhead 1 for zone B, which demonstrated a maximum error of approximately 12.6 cm. As a result, this camera angle was not used in subsequent video analysis. The average maximum uncertainty (±) error for the 3D helmet tracks was lowest for orthogonal camera angles (range: 0.6–1.6 cm), whereas parallel camera angles had the highest levels of uncertainty (range: 4.3–10.0 cm) that were considerably greater than the average maximum errors across all test conditions (≤ 2.4 cm).

Average resultant impact velocity, as measured from 3D video analysis, and calculations of RE, AE and RMSE for all test conditions are summarized in Table 4.2. With respect to camera angle, the parallel configurations consistently had the highest errors (RE, AE: 3.79–10.94%; RMSE: 0.18–0.55 m/s), overpredicting impact velocity regardless of the zone or impact speed (zone A: 104% at 4.69 m/s [slow], 107% at 6.40 m/s [fast]; zone B: 111% at 5.01 m/s [slow], 107% at 6.39 m/s [fast]). This was largely attributable to the inaccuracies of the estimated impact velocities in the horizontal plane, specifically along the *y*-axis (i.e., parallel to yard lines). Horizontal velocity values should have equaled 0 m/s during free fall; however, the absolute magnitude of $(V_0)_y$ across all parallel test conditions averaged 1.52 m/s compared to 0.04 m/s for $(V_0)_x$ (Table 4.3). All remaining camera angles collectively had ≤ 3.39% difference for RE and AE between the video tracked and reference impact velocities, and RMSEs of ≤ 0.22 m/s.

Table 4.2 – Average (±SD) resultant helmet impact velocity and error measures across available camera angles for each zone and impact speed.

		Zone A							Zone B						
		Impact Velocity (m/s)			Error				Impact Velocity (m/s)			Error			
Drop Test	Camera Angle	V_{drop}	V_{video}	(±SD)	RMSE (m/s)	RE (%)	AE (%)	CV (%)	V_{drop}	V_{video}	(±SD)	RMSE (m/s)	RE (%)	AE (%)	CV (%)
Slow	Orthogonal	4.52	4.50	(0.05)	0.05	-0.49	0.83	1.13	4.52	4.48	(0.06)	0.06	-0.84	1.00	1.24
	Coincident	-	-	-	-	-	-	-	4.52	4.45	(0.11)	0.11	-1.48	2.31	2.40
	Parallel	4.52	4.69	(0.08)	0.18	3.79	3.79	1.70	4.52	5.01	(0.30)	0.55	10.94	10.94	6.04
	Overhead 1	4.52	4.54	(0.05)	0.04	0.49	0.93	1.01	-	-	-	-	-	-	-
	Overhead 2	4.52	4.57	(0.06)	0.07	1.09	1.17	1.21	4.52	4.46	(0.05)	0.07	-1.42	1.42	1.05
Fast	Orthogonal	5.99	6.13	(0.11)	0.17	2.33	2.33	1.85	5.99	6.08	(0.13)	0.14	1.54	1.54	2.10
	Coincident	-	-	-	-	-	-	-	5.99	6.02	(0.04)	0.04	0.49	0.64	0.68
	Parallel	5.99	6.40	(0.22)	0.45	6.86	6.86	3.38	5.99	6.39	(0.26)	0.45	6.60	6.60	4.00
	Overhead 1	5.99	6.19	(0.09)	0.22	3.39	3.39	1.47	-	-	-	-	-	-	-
	Overhead 2	5.99	6.08	(0.09)	0.12	1.54	1.54	1.47	5.99	6.05	(0.05)	0.07	0.99	0.99	0.86

Note: V_{drop} = reference impact velocity derived from Equation 1; V_{video} = estimated impact velocity from 3D video tracking; RMSE = root-mean-square error; RE = relative error; AE = absolute error; CV = coefficient of variation.

Table 4.3 – Average (±SD) horizontal and vertical helmet impact velocities across available camera angles for each zone and impact speed.

		Impact Velocity (m/s)											
		Zone A						Zone B					
Drop Test	Camera Angle	$(V_0)_x$		$(V_0)_y$		$(V_0)_z$		$(V_0)_x$		$(V_0)_y$		$(V_0)_z$	
Slow	Orthogonal	-0.01	(0.01)	-0.03	(0.01)	-4.50	(0.05)	-0.10	(0.02)	-0.06	(0.02)	-4.48	(0.06)
	Coincident	-	-	-	-	-	-	-0.10	(0.02)	-0.19	(0.08)	-4.45	(0.10)
	Parallel	-0.02	(0.02)	0.48	(1.47)	-4.51	(0.06)	-0.03	(0.01)	1.96	(1.01)	-4.55	(0.13)
	Overhead 1	0.01	(0.01)	0.14	(0.01)	-4.54	(0.05)	-	-	-	-	-	-
	Overhead 2	0.27	(0.06)	-0.03	(0.02)	-4.56	(0.05)	-0.13	(0.05)	-0.05	(0.01)	-4.45	(0.05)
Fast	Orthogonal	0.01	(0.02)	-0.05	(0.02)	-6.13	(0.11)	-0.10	(0.03)	-0.09	(0.05)	-6.08	(0.13)
	Coincident	-	-	-	-	-	-	-0.10	(0.03)	-0.13	(0.10)	-6.02	(0.04)
	Parallel	-0.05	(0.03)	-1.77	(1.28)	-6.06	(0.08)	-0.04	(0.01)	-1.87	(1.12)	-6.04	(0.05)
	Overhead 1	0.01	(0.02)	0.19	(0.01)	-6.19	(0.09)	-	-	-	-	-	-
	Overhead 2	0.37	(0.11)	-0.06	(0.05)	-6.07	(0.09)	-0.18	(0.04)	-0.07	(0.06)	-6.05	(0.05)

Note. $(V_0)_x$ = horizontal impact velocity (*x*-axis: parallel to side lines); $(V_0)_y$ = horizontal impact velocity (*y*-axis: parallel to yard lines); $(V_0)_z$ = vertical impact velocity (*z*-axis: orthogonal to the field surface).

Matching camera angles between the two test zone locations (i.e., orthogonal, overhead 2) demonstrated comparable levels of accuracy for both impact speeds despite the increased camera distances. Fast drop tests generally had higher errors than slow drop tests for the same camera pair; although, these differences were relatively small when excluding parallel angles, with varied results in zone B. The CVs for the three impact trials analyzed across the available camera angles in each zone ranged from 0.68 to 6.04%, demonstrating good reliability of the video tracking process.

Average RMSE of resultant helmet velocity time-histories over a window of 150 ms pre-impact from V_0 was ≤ 0.16 m/s and ≤ 0.26 m/s for zone A and zone B, respectively, when considering all impact speeds and camera angles except parallel (range: 0.60–1.06 m/s) (Figure 4.4). Similar to the findings for helmet impact velocity (V_0), evaluation of the pre-impact helmet velocities in each direction showed that values along the *y*-axis contributed to most of the error overall, with RMSEs ranging from 1.92 to 2.97 m/s for each zone and impact speed (Table 4.4).

Discussion

The purpose of the present study was to assess the validity of a multi-camera videogrammetry approach used to quantify helmet velocities in the context of youth football helmet-to-ground impacts (Chapter 2). The effects of camera angle, camera distance and impact speed on the accuracy of 3D video tracking were investigated using free fall drop tests of a helmeted ATD head and neck assembly within two test zones on a football field. Overall, with the exception of parallel camera angles, impact velocities

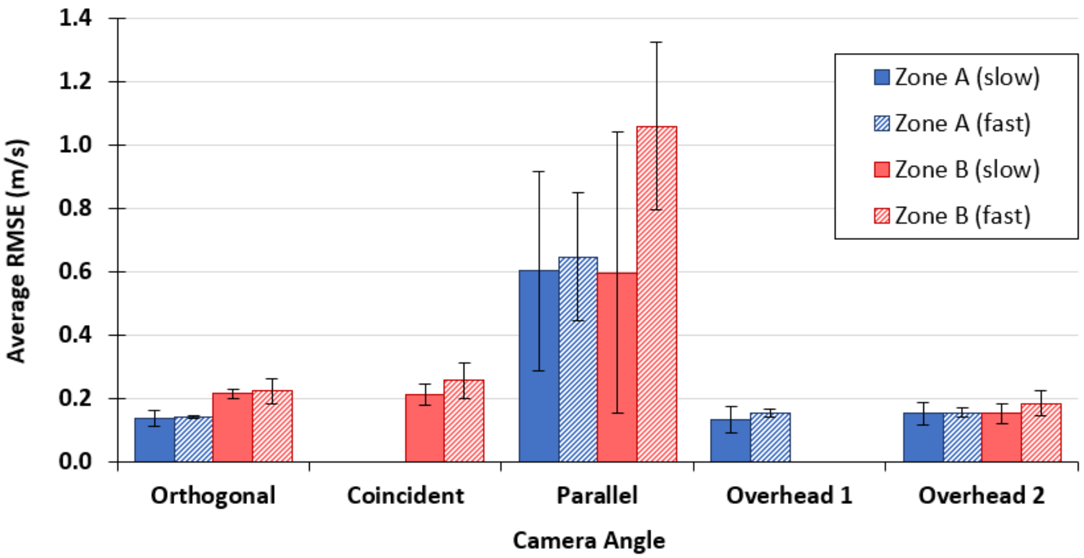

Figure 4.4 – Average (±SD) root-mean-square error (RMSE) for resultant helmet velocity time-histories over a window of 150 ms pre-impact from V_0 across the camera angles available for each zone and impact speed.

Table 4.4 – Average root-mean-square error (RMSE) for horizontal and vertical helmet velocity time-histories over a window of 150 ms pre-impact from V_0 across available camera angles for each zone and impact speed.

		RMSE (m/s)					
		Zone A			Zone B		
Drop Test	Camera Angle	V_x	V_y	V_z	V_x	V_y	V_z
Slow	Orthogonal	0.00	0.02	0.14	0.05	0.05	0.22
	Coincident	-	-	-	0.05	0.11	0.21
	Parallel	0.03	2.08	0.22	0.01	1.92	0.22
	Overhead 1	0.01	0.10	0.14	-	-	-
	Overhead 2	0.19	0.03	0.15	0.12	0.05	0.16
Fast	Orthogonal	0.02	0.03	0.14	0.06	0.06	0.22
	Coincident	-	-	-	0.06	0.11	0.26
	Parallel	0.04	2.34	0.20	0.03	2.97	0.21
	Overhead 1	0.03	0.13	0.16	-	-	-
	Overhead 2	0.28	0.04	0.16	0.14	0.06	0.19

Note. V_x = horizontal velocity (*x*-axis: parallel to side lines); V_y = horizontal velocity (*y*-axis: parallel to yard lines); V_z = vertical velocity (*z*-axis: orthogonal to the field surface).

measured from the video analysis compared favorably to the reference velocities (slow: 4.50 ± 0.05 m/s; fast: 6.09 ± 0.06 m/s) with relatively low errors across all test conditions (RE: -1.48–3.39%; AE: 0.64–3.39%; RMSE: 0.04–0.22 m/s). These findings were reflected in the helmet velocity time-histories over a 150 ms window leading to V_0, wherein average RMSE for parallel camera angles (0.60–1.06 m/s) were greater than the remaining test conditions combined (0.13–0.26 m/s). Increasing the camera distance of matching camera angles between zones (i.e., orthogonal, overhead 2) did not appreciably influence 3D video tracking accuracy; increasing the drop test impact speed produced only slightly higher error estimates for the majority of camera pairs.

In general, the results of this study demonstrated the effectiveness of several different camera angles for tracking 3D helmet motion with this videogrammetry approach. Orthogonal camera angles regularly had the lowest calibration and uncertainty error overall, suggesting that it may be the optimal choice for precise 3D measurement. Consequently, incorporating more field-level cameras could help improve this approach by increasing the likelihood of capturing an impact event with a pair of orthogonal views, or with a coincident camera angle (e.g., zone B), which also exhibited high-levels of accuracy. Overhead camera angles were found to have relatively low error when paired with a field-level camera as well, suggesting that the inclusion of an overhead camera view could improve field coverage. However, as observed with the high calibration error for the overhead 1 camera angle in zone B, it can be surmised that sufficient angular separation from the field-level camera view would be required to establish an acceptable 3D field coordinate system for video analysis. Despite adequate calibration error for parallel camera angles (even with the linearity of the camera views), the large uncertainty errors for the 3D position coordinates translated to the highest errors for the helmet velocity estimates; these were mainly attributable to inaccuracies in the y-axis measurements (i.e., across the field). Based on these findings, the best practice when selecting combinations of camera views for this videogrammetry approach would be to avoid the use of parallel camera angles, where possible.

No notable differences in estimated error were observed in this study when the distance from the impact event for the orthogonal and overhead 2 camera angles was increased. While promising, this outcome is likely because the selected method of validating helmet velocities (i.e., free fall drop tests) only produced pre-impact motion in the vertical plane. As a result, the effect of the direction of motion relative to the camera views was not assessed, and evaluation of the horizontal (or ground plane) velocities was limited to calculating deviations from 0 m/s. Prior validation work tracking helmet motion with single camera-systems has reported larger measurement error for movement towards or away from the camera (Campolettano et al., 2018; Post et al., 2018). Although this study involved 3D video analysis, helmet motion was mainly orthogonal to all camera perspectives, which may have inherently reduced error in the video tracking process by removing the difficulty of accurately digitizing movements in-line with the camera perspective. However, the goal of using the drop tests was to simulate a helmet-to-ground impact and, unlike the validation methods used by Bailey et al. (2018), staging on-field helmet-to-ground impacts by launching an ATD off a belt-driven sled and tracking helmet kinematics with a motion capture system was not within the scope of this research.

Helmet impact velocity estimations from the two pre-determined drop test heights were found to be accurate for both impact speeds analyzed. Most camera pairs displayed a marginal increase in error for fast drop tests compared to the corresponding slow drop tests, and the magnitudes of the fast impact velocities were consistently overpredicted. This finding is not entirely surprising considering that the precision with which one can accurately extract kinematic measurements from video is dependent on several factors (e.g., frame rate, image resolution, motion blur, etc.) that can be influenced by the speed of the object being tracked. Therefore, while it could be postulated that this videogrammetry approach may demonstrate increased error for impact events of higher velocities, the reference velocities assessed in this study fall within the ranges of individual player velocities reported for helmet-to-ground (1.94–6.69 m/s) (Chapter 2) and helmet-to-helmet (0.2–5.4 m/s) (Campolettano et al., 2018) impacts in youth football.

Overall, in spite of differing validation procedures, estimated errors associated with this multi-camera videogrammetry approach were found to be comparable to previously published studies using video to quantify 3D helmet velocities in football. Relative and absolute errors of impact velocity estimations from the drop tests in the current study were less than 4% across all test conditions (except certain parallel camera angles). In comparison, validation of the videogrammetry technique used by Pellman al. (2003) for analyzing NFL helmet impacts included three test scenarios in which helmeted volunteers drove motorized utility carts at three different locations on the field, each in a different direction of motion (Newman et al., 2005). Direct measurement of the cart speeds showed that the error of the corresponding closing speeds estimated from video ranged from 1.2 to 11.3% (Newman et al., 2005). The MBIM technique developed and validated by Bailey et al. (2018) to analyze helmet kinematics in the NFL showed that low frame rate video (60 Hz) was sufficient for measuring pre-impact translational helmet velocity. Video in the present study was recorded at 120 Hz, double the minimum frame rate proposed by Bailey et al. (2018) for accurate measurement of helmet velocity prior to impact. Furthermore, in contrast to the panning and zooming lenses commonly employed for video analysis from NFL broadcast game footage (Bailey et al., 2020; Kent et al., 2020; Pellman et al., 2003), cameras in this multi-camera videogrammetry approach were stationary with fixed lenses, effectively eliminating issues of cumulative uncertainty and distortion.

The research presented here has limitations related to its methodology that should be acknowledged. Although gravity-driven tests can offer high levels of repeatability in a laboratory environment, data collection for this study took place on an outdoor football field. As a result, exposure to inclement weather (e.g., strong winds) could not be avoided, and may have impacted the drop test conditions and video recordings. For the purpose of this study, air resistance was considered to be negligible. Furthermore, cameras were mounted on heavy, reinforced stands to mitigate potential image stabilization issues; subsequently, very minor wind shake was temporarily noted for only a few video clips. In addition, the use of videogrammetry to measure 3D helmet velocities can be influenced by several factors during post-processing of the video data; this includes potential human error related to the manual digitization of tracking helmet motion as well as setting the 3D field coordinate systems. However, helmet impact velocity estimations for the three repeated drop trials in each test condition demonstrated good reliability.

In summary, the multi-camera videogrammetry approach provided accurate measurements of 3D helmet velocity from simulated helmet-to-ground impacts. The findings demonstrate the effectiveness of multiple combinations of both field-level and overhead camera views for tracking 3D helmet motion, however, inaccuracies with horizontal measurements in-line with parallel camera views need to be recognized. Increased camera distance did not greatly influence velocity estimates; although, capturing impact events closer to the camera views is innately better for precise video analysis. While this study supports prior video analysis work in youth football (Chapter 2), future research should consider adapting this multi-camera approach to measure helmet (or head) velocity across different contact sports (e.g., soccer, hockey, etc.), thereby providing further insight into biomechanics of in-game impacts that occur in untelevised youth sport populations.

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CHAPTER 5

CHALLENGES OF RECONSTRUCTING CASES OF IN-GAME HELMET-TO-GROUND IMPACTS IN YOUTH FOOTBALL

Introduction

Laboratory reconstructions of sport-related helmet impacts are an important research method that can provide valuable insight into the biomechanics of head injury. In the context of football, such efforts have been limited to reconstructing cases of severe or concussive on-field helmet impacts observed in National Football League (NFL) games (Cournoyer & Hoshizaki, 2021; Funk et al., 2020; Jadischke et al., 2018; Karton et al., 2020; Kent, Forman, Bailey, Funk, et al., 2020; Newman et al., 1999; Newman et al., 2000; Pellman, Viano, Tucker, Casson, & Waeckerle, 2003). These studies have been conducted across different types of impact (e.g., helmet-to-helmet, helmet-to-ground, helmet-to-shoulder, etc.) with varying levels of complexity (Table 5.1). However, the general methodology remains the same, in which video analysis techniques are used in combination with instrumented anthropomorphic test devices (ATDs) and test apparatuses to replicate the conditions of helmet impact. The kinematic parameters derived from these reconstructions can provide valuable information related to the impact response of the head, such as translational and rotational acceleration-time curves, which can then be applied to various injury risk functions or finite-element models to examine the relationship between head motion and tissue-level predictors of brain injury.

Table 5.1 – Laboratory reconstructions of concussive and severe NFL helmet impacts (extended on next page).

Study	Helmet Impact Cases	Video Analysis	Anthropomorphic Test Device	Test Apparatus
Newman et al. (1999, 2000)	- Helmet-to-helmet (*n* = 12) - concussion cases (*n* = 9) - 1995–1999 NFL seasons	3D	*Helmet-to-helmet* - Struck player: HIII head/neck - Striking player: HIII head/neck/torso	*Helmet-to-helmet* - Monorail drop tower: HIII head/neck guided in free fall onto a freely suspended HIII head/neck/torso
Pellman, Viano, Tucker, Casson, & Waeckerle (2003)	- Helmet-to-helmet (*n* = 27) - Helmet-to-ground (*n* = 4) - Concussion cases (*n* = 25) - 1996–2001 NFL seasons	3D (Newman et al., 1999)	*Helmet-to-helmet* - Struck player: HIII head/neck/torso - Striking player: HIII head/neck *Helmet-to-ground* - Struck player: HIII head/neck	*Helmet-to-helmet* - Monorail drop tower: HIII head/neck guided in free fall onto a freely suspended HIII head/neck/torso *Helmet-to-ground* - Monorail drop tower: HIII head/neck guided in free fall onto a simulated ground surface
Funk et al. (2020)	- Helmet-to-helmet (*n* = 17) - Concussion cases (*n* = 16) - 2015–2017 NFL seasons	3D, MBIM (Bailey et al., 2018)	*Helmet-to-helmet* - Struck and striking player: HIII head/neck/torso with pedestrian pelvis - HIII lower neck mount modified in some cases (spherical ball joint for lateral flexion and twist of the neck)	*Helmet-to-helmet* - Custom belt-driven sleds: Two moving HIII head/neck/torso/pelvis propelled into each other (15 cases); one moving HIII head/neck/torso/pelvis propelled into a stationary HIII head/neck/torso/pelvis (2 cases)
Karton et al. (2020)	- Helmet-to-helmet (*n* = 72) - Helmet-to-shoulder (*n* = 62) - Helmet-to-hip/thigh (*n* = 25) - Helmet-to-ground (*n* = 90) - 32 games, 2009–2015 NFL seasons	2D (Post et al., 2018)	*Helmet-to-helmet* - Struck player: HIII head/neutral unbiased neck (Walsh et al., 2018) - Striking player: HIII head/neck *Helmet-to-shoulder, Helmet-to-hip/thigh and helmet-to-ground* - Struck player: HIII head/neutral unbiased neck (Walsh et al., 2018)	*Helmet-to-helmet* - Pneumatic linear impactor: HIII head/neck attached to impactor arm and HIII head/neutral unbiased neck attached to a sliding table *Helmet-to-shoulder* - Pneumatic linear impactor: vinyl nitrile foam and football shoulder pad attached to impactor arm HIII head/neutral unbiased neck attached to sliding table *Helmet-to-hip/thigh* - Pneumatic linear impactor: vinyl nitrile foam attached to impactor arm and HIII head/neutral unbiased neck attached to sliding table *Helmet-to-ground* - Monorail drop tower: HIII head/neutral unbiased neck guided in free fall onto a simulated turf surface

Table 5.1– Laboratory reconstructions of concussive and severe NFL helmet impacts (extended from previous page).

Kent, Forman, Bailey, Funk, et al. (2020)	- Concussive helmet-to-ground ("whipping" kinematic; 3 conditions: back, side and facemask) - NFL season(s) not reported	3D; MBIM (Bailey et al., 2018)	*Helmet-to-ground* - Struck player: HIII head/neck/torso with pedestrian pelvis	*Helmet-to-ground* - Custom belt-driven sleds: HIII head/neck/torso/pelvis propelled horizontally and allowed to fall under gravity onto the field surface in an NFL football stadium
Cournoyer & Hoshizaki (2021)	- Helmet-to-helmet (*n* = 21) - Helmet-to-ground (*n* = 5) - Helmet-to-shoulder (*n* = 15) - 2 concussion groups with and without loss of consciousness (82 injury reconstructions total)	2D (Post et al., 2018)	*Helmet-to-helmet* - Struck player: HIII head/neutral unbiased neck (Walsh et al., 2018) - Striking player: HIII head/neck *Helmet-to-shoulder and helmet-to-ground* - Struck player: HIII head/neutral unbiased neck (Walsh et al., 2018)	*Helmet-to-helmet* - Pneumatic linear impactor: HIII head/neck attached to impactor arm and HIII head/neutral unbiased neck attached to sliding table *Helmet-to-shoulder* - Pneumatic linear impactor: vinyl nitrile foam and football shoulder pad attached to impactor arm and HIII head/neutral unbiased neck attached to sliding table *Helmet-to-ground* - Monorail drop tower: HIII head/neutral unbiased neck guided in free fall onto a simulated turf surface

Note. HIII = Hybrid III 50th percentile male; MBIM = model-based image-matching.

To the author's knowledge, there has not been any comparable reconstruction work for helmet impacts in the youth football population. The current dissertation was built on the theme of assessing the biomechanics of in-game youth football helmet impacts using a three-dimensional video-based methodology. A natural progression of this work would therefore be to apply the descriptive and kinematic data acquired from Chapter 2 to identify cases of helmet-to-ground impact that could be eligible for potential laboratory reconstruction. The following Chapter highlights some of the key methodological considerations to reconstruct these helmet impacts with an acceptable level of accuracy.

Methodological Considerations

Equipment

Anthropometric test device. Anthropomorphic test devices, commonly known as crash test dummies, are mechanical human surrogates designed to measure the response of the body to injurious crash (or impact) events. Throughout the literature, the Hybrid III (HIII) 50th percentile male ATD has been the standard surrogate used for laboratory reconstruction work replicating helmet impacts experienced by NFL players (Cournoyer & Hoshizaki, 2021; Funk et al., 2020; Jadischke et al., 2018; Karton et al., 2020; Kent, Forman, Bailey, Funk, et al., 2020; Newman et al., 1999; Newman et al., 2000; Pellman, Viano, Tucker, Casson, & Waeckerle, 2003). However, if the aim is to reconstruct cases of helmet impact at the youth-level (≤ 14 years), one must consider the physical differences in body dimensions and weight proportions of professional athletes (i.e., adults) compared to the youth athletes when selecting an ATD. For the sample of youth football players assessed in the present dissertation, the technical specifications of the

HIII 5th percentile female ATD would offer a more biofidelic option as the total mass of the dummy (108.03 ± 2.0 lbs; 49.0 ± 0.91 kg) is representative of the average weights of 13- and 14-year-old Canadian males (Dieticians of Canada, 2014), and the head circumference (21.2 in; 53.9 cm) matches the fit guidelines for various small and medium sized youth football helmets.

It is also important to note that the HIII family of ATDs is specifically designed for testing automotive restraint systems in frontal crash scenarios. This impact scenario involves fundamentally different mechanics than H2G impacts observed in football, wherein the distribution of (ground) contact to the head is primarily concentrated on the rear and side regions of the helmet (Chapter 2 and 4; Bailey et al., 2020; Kent, Forman, Bailey, Funk, et al., 2020; Pellman, Viano, Tucker, & Casson, 2003) Since this is not how these ATDs were intended to be impacted, repeated exposure to rear or lateral loading conditions could compromise the structural integrity of the equipment. In particular, the segmented rubber on the HIII neck forms may degrade more rapidly (i.e., tear) following H2G simulations involving repetitive contact to the rear of the helmet and excessive neck flexion, which could influence the impact response biofidelity. For youth reconstructions, this concern would be further compounded by the fact that the HIII 5th percentile female neck form is significantly more compliant, and less robust, than the HIII 50th percentile male neck form. Therefore, careful inspection of the neck form may be warranted when reconstructing youth H2G impacts to ensure consistent ATD performance, especially since a couple of the H2G impact cases from Chapter 2 demonstrated resultant impact velocities exceeding 6 m/s.

***Test apparatus*.** Another important consideration for H2G impact reconstructions in football, regardless of the age group being assessed, is the test apparatus used to simulate the mechanism of helmet contact with the ground. Whole-body kinematics of concussive or severe H2G impacts in NFL games have described a "whipping" motion into the ground, similar to that of a backwards pitching fall (Figure 5.1) (Kent, Forman, Bailey, Funk, et al., 2020; Lessley et al., 2018). This specific mechanism has been observed for non-injurious H2G impacts in youth football games as well (Chapter 2). To date, the majority of NFL H2G reconstructions have employed a monorail drop tower to impact a HIII head and neck assembly onto simulated ground (or turf) surface

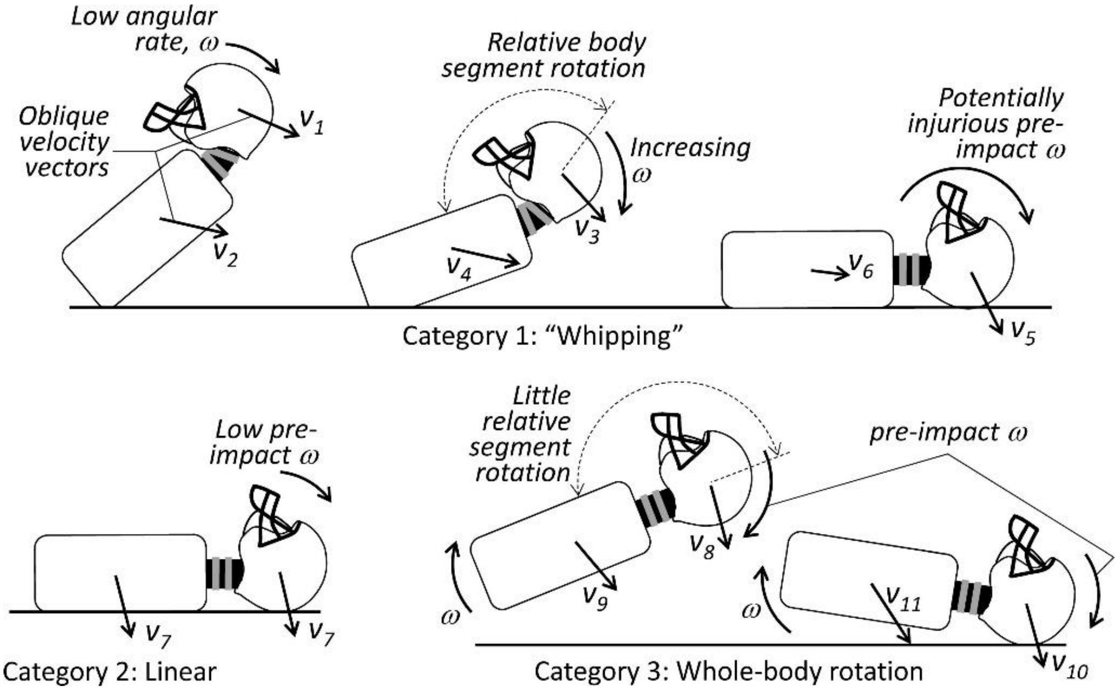

Figure 5.1 – Illustration of the three general kinematical categories identified by Kent, Foreman, Bailey, Funk, et al. (2020) for concussive helmet-to-ground impacts in the NFL, including the "whipping" kinematic (Category 1). Reprinted from Journal of Biomechanics, 99, Kent, R., Forman, J., Bailey, A. M., Funk, J., Sherwood, C., Crandall, J., Arbogast, K. B., & Myers, B. S, The biomechanics of concussive helmet-to-ground impacts in the National Football League, 1–7, Copyright (2020), with permission from Elsevier.

(Cournoyer & Hoshizaki, 2021; Karton et al., 2020; Pellman, Viano, Tucker, Casson, & Waeckerle, 2003). While this approach aligns with current helmet performance test standards (i.e., drop tests), it is limited in its capacity to represent the key characteristics of H2G impact, including the rotational motion of the head and loading of the neck prior to ground impact, oblique impact velocity vectors, as well as the effect of impact surface compliance and friction (Kent, Forman, Bailey, Cormier, et al., 2020). In response to this, new modifications have been proposed to improve the capabilities of standard rail-based drop towers for replicating the mechanics of H2G impact (i.e., the addition of a pivoting neck mount and curvilinear bearing track) (Kent, Forman, Bailey, Cormier, et al., 2020), but have yet to be used for reconstruction purposes.

Currently, one of the more realistic methods of simulating a H2G impact in football involves the use of a belt-driven sled to launch a partial ATD (composed of a HIII head, neck, torso and pedestrian pelvis) from a specified drop height and horizontal velocity onto a field (Bailey et al., 2018; Kent, Forman, Bailey, Funk, et al., 2020). A main advantage of this method is that the head of the ATD can be positioned slightly above the pelvis such that the initial interaction of the pelvis with the ground (followed by the torso) naturally induces the desired “whipping” kinematic of the head. Moreover, unlike drop tower systems, which only utilize a head and neck assembly, the use of a partial ATD as the human surrogate incorporates the effect of head and neck coupling with the body into the impact response. However, while this lab-based launch system may better represent real-world H2G impact conditions in football, it is not practical for most researchers and involves techniques that fall outside of conventional helmet impact testing practices.

Input parameters

When designing a laboratory reconstruction, the primary objective is to replicate the impact conditions as closely as possible. Reconstructions of NFL impacts to date have relied on the analysis of game video to guide the experimental set-ups, wherein input parameters such as helmet impact velocity, location and orientation are determined to provide a detailed kinematic description of the impact event.

Impact velocity. Various video analysis techniques have been used in the literature to measure the impact (or closing) velocity of reconstructed NFL impact cases. Generally, these studies employed videogrammetry to quantify three-dimensional (3D) helmet velocities from two or more camera views of broadcast game video (Funk et al., 2020; Kent, Forman, Bailey, Funk, et al., 2020; Newman et al., 1999; Pellman, Viano, Tucker, Casson, & Waeckerle, 2003); however, some have relied on two-dimensional (2D) helmet velocity estimates from low-frame rate video captured from a single-camera view (Cournoyer & Hoshizaki, 2021; Karton et al., 2020). Under most conditions, a single-camera system is not an appropriate option to acquire accurate estimations of real-world impact kinematics; a multi-camera system is necessary to understand 3D velocities with certainty. Consequently, the 3D helmet velocities derived from the videogrammetry approach described in Chapter 2 should provide a sufficient level of accuracy for reconstructing the cases of youth football H2G impact.

Impact location and orientation. An additional aspect of video analysis in prior NFL reconstruction work was to assist in matching the helmet contact location and player orientation during the game impact as closely as possible. This has been accomplished using a few different methods, the level of precision of which is influenced by the video analysis techniques employed (single- vs multi-camera system) and the limitations imposed by the experimental set-up (ATD assembly, test apparatus, laboratory space available, etc.). Earlier studies used two high-speed cameras to record the laboratory reconstructions at the same relative angles observed in the camera views from the game video (Newman et al., 1999; Newman et al., 2000; Pellman, Viano, Tucker, Casson, & Waeckerle, 2003). In this way, an approximated one-to-one comparison could be used to adjust the configuration of the ATD to mimic the game situation. Karton et al. (2020) used a more simplified approach, wherein the helmet was divided into sectors (top view) and levels (side view) to determine the general impact location, with the impact direction and post-impact head motion verified with a single high-speed camera. According to the authors, this method was deemed appropriate since the estimated impact orientation was within a tolerance of 15°, and smaller increments have shown little effect on the dynamic response of the HIII headform (Oeur et al., 2014; Walsh et al., 2011); however, this justification was specific to pneumatic linear impactor testing with a HIII 50th percentile male ATD. Therefore, sensitivity testing for simulated H2G impacts for youth players may present different results. Model-based image-matching has also been used to track the frame-by-frame position and orientation of the helmeted head (and torso) relative to the field in six degrees of freedom (Funk et al., 2020; Jadischke et al., 2018). While this advanced method offers objective kinematic data to match the impact conditions from the game video, it is beyond the scope of the video analysis technique utilized in Chapter 2.

Output parameters

The validation of laboratory reconstructions is often assessed by the accuracy of the output parameters. Across the majority of studies that reconstructed NFL impacts, matching the post-impact motion of the ATD to the player in the game video was the most common output parameter reported to verify reconstructions (Funk et al., 2020; Jadischke et al., 2018; Karton et al., 2020; Newman et al., 1999; Newman et al., 2000; Pellman, Viano, Tucker, Casson, & Waeckerle, 2003). Acquiring the correct head kinematics to inform youth H2G reconstructions could prove to be challenging. First, given the compliance of the HIII 5th neck form and the inability to replicate muscle force activations, it is possible that significantly more neck flexion may occur after ground impact in the reconstruction compared to the game video. Second, as noted in Chapter 2, the post-impact head kinematics of the youth H2G impacts differed across the cases that were analyzed, with some experiencing a dynamic helmet rebound off the ground and others maintaining contact with the ground (i.e., sliding along the turf) until their motion had arrested. Moreover, experimental design details, such as the mechanical properties (i.e., stiffness) of the simulated impact surface, would influence the ATD response following impact as well.

Impact-induced change in helmet velocity was calculated in Chapter 2. As a result, an output parameter associated with the velocity change (ΔV) of the helmeted ATD could also potentially be used to validate the laboratory reconstructions, as per the concussive H2H impact reconstructions performed by Funk et al. (2020). However, the postulated difficulties related to matching post-impact motion mentioned above could, in turn, affect the ability to effectively use the change in helmet velocity as an output parameter. In addition, due to the relative motion that occurs between the helmet and head during a football impact (Joodaki et al., 2019), the ΔVs of the helmet and head cannot be directly compared; therefore, additional 3D motion tracking of the helmet would need to be implemented during the reconstruction to use the measurements from video analysis as validation. Lastly, head acceleration data were not collected during the youth football games analyzed in Chapter 2, and therefore, it could not be used as an output parameter in future reconstructions. Although, as indicated previously, the accuracy of the sensor-based technology used to measure the magnitudes of in-game head impacts (e.g., instrumented helmets) is questionable in its own right (Jadischke et al., 2013; Joodaki et al., 2019; Siegmund et al., 2016).

Conclusion

In summary, the descriptive and kinematic data from the video analysis in Chapter 2 of this dissertation offers a foundation on which cases of H2G impact in youth football games can be reconstructed, similar to what has been previously achieved in the NFL (Cournoyer & Hoshizaki, 2021; Funk et al., 2020; Jadischke et al., 2018; Karton et al., 2020; Kent, Forman, Bailey, Funk, et al., 2020; Newman et al., 1999; Newman et al., 2000; Pellman, Viano, Tucker, Casson, & Waeckerle, 2003). Conducting this type of research is a technically challenging process that requires the consideration of multiple factors (e.g., equipment, input and output parameters, etc.) in order to replicate real-world impact conditions as accurately as possible, especially given the unique mechanisms associated with H2G impact in football. Balancing the precision of the experimental design with the available resources, cost and time of pursing this effort also requires deliberation, as there appears to be no one accepted approach to conducting these reconstructions. Nonetheless, laboratory impact reconstructions focused on youth football players represent an important next step in the continued effort to improve our understanding of helmet impact biomechanics in this population and better protect these athletes from head injury, such as concussion.

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CHAPTER 6

DISCUSSION AND CONCLUSIONS

In a high-contact sport, such as football, biomechanical research has been integral for improving player safety through the analysis and interpretation of the mechanisms of in-game helmet impacts. It has only been within the last decade that studies focusing on helmet impacts in youth football populations (≤ 14 years) have emerged in the literature, despite the large number of players participating at this age level across North America. Sensor-based methods using instrumented helmets equipped with accelerometer arrays have largely dominated these research efforts in youth football (Campolettano et al., 2017; Cobb et al., 2013; Daniel et al., 2012, 2014; Kelley, Kane, et al., 2017; Kelley, Urban, et al., 2017; Munce et al., 2015; Young et al., 2014); in contrast, video-based methods have been notably limited in both number and scope (i.e., single-camera systems). The use of video analysis techniques for investigating football helmet impacts has focused almost exclusively on concussive impacts in National Football League (NFL) games due to the high-quality, multi-view video available for assessment (e.g., broadcast footage) (Bailey et al., 2020; Clark et al., 2017; Kent et al., 2020; Lessley et al., 2018; Lessley et al., 2020; Pellman, Viano, Tucker, & Casson, 2003; Pellman, Viano, Tucker, Casson, & Waeckerle, 2003). Therefore, the objective of this dissertation was to develop, validate and apply a multi-camera approach (adapted from (Jadischke et al., 2020)) to conduct descriptive and quantitative video analyses of helmet impacts occurring in youth football games. The contributions of this video-based work aim to advance our understanding of helmet impact biomechanics experienced by youth football players such that helmet test standards and design can better represent the on-field impact conditions occurring at the youth-level, thereby improving athlete safety and protection.

Video of three youth football games from two age divisions (game A: 9–12 years; games B and C: 13–14 years) was recorded using a multi-camera approach; this consisted of 11 stationary action cameras (2.7 K, 120 fps, shutter speed 1/1920 s, 41° field of view (Jadischke et al., 2019)) positioned around half of the field of play such that the number and quality of available camera views on the targeted area was optimized. In Study 1 (Chapter 2), a videogrammetric technique was used to quantify three-dimensional (3D) helmet kinematics associated with 21 non-injurious helmet-to-ground (H2G) impact cases (9–12 years: $n = 9$; 13–14 years: $n = 12$). Each impact case possessed its own set of unique characteristics preceding the helmet strike to the ground, but the majority followed a B2B (body-to-body)-B2G (body-to-ground)-H2G contact progression, wherein the whole-body kinematics of the players often resembled the general "whipping" motion observed for H2G concussions in professional football (Kent, Forman, Bailey, Funk, et al., 2020). In general, the average pre-impact velocity (4.04 ± 1.24 m/s) and impact-induced change in velocity (3.32 ± 1.14 m/s) of these non-injurious, youth football H2G impacts were notably lower in magnitude than previously reported 3D helmet kinematics for injurious (i.e., concussive) H2G impacts in the NFL (Bailey et al., 2020; Kent et al., 2020; Pellman, Viano, Tucker, Casson, & Waeckerle, 2003); these values did however share some similarities to un-helmeted, non-injurious H2G contacts in American 7v7 non-tackle football (Jadischke et al., 2020). Additionally, the impact severity (ΔV) of the sample of H2G impact cases in this study suggests that the drop test conditions proposed by the National Operating Committee on Standards for Athletic

Equipment (NOCSAE) for the new youth football helmet standard may not be representative of in-game impacts experienced by youth players. Impact velocities of these drop tests range between 3.46 to 5.46 m/s (NOCSAE, 2020), and with helmet rebound, this can result in ΔVs of the headform surpassing 8.0 m/s, which is significantly more severe than the results reported in this work.

A descriptive video analysis was performed in Study 2 (Chapter 3) to describe the mechanisms and situational factors associated with in-game helmet impacts experienced by youth football players. The same multi-view video from the three youth football games was reviewed and parameters related to all cases of observed helmet impact (injury and non-injury) were documented. Helmet impact cases generally occurred during a rush play (67.4%) and were mainly concentrated in the mid-field (81%), reflecting the level-of-play at the youth level. A unique finding of this study showed that the most common source of helmet contact for youth players was with the ground (59.1%), which opposes the limited (single-camera) video analysis work for youth football (Alois et al., 2019; Le et al., 2021). Together, the rear (upper) and side (upper) regions of the helmet accounted for 56.5% of all observed helmet contacts and 81% of H2G contacts. The over-representation of these helmet contact locations for H2G impacts parallels the results from the video analysis of concussive impacts in NFL games (Lessley et al., 2018), suggesting that the performance of these helmet regions for attenuating ground impact forces should be considered in helmet certification standards and helmet design. Tackling an opposing player was the most frequent activity leading to helmet impact (41.1%) in general, with 25% of all cases specifically related to H2G impacts when tackling. Therefore, further investigation of youth tackling techniques and helmet interaction with the ground may be warranted.

Study 3 (Chapter 4) presented the validation of a multi-camera videogrammetry approach for measuring 3D helmet impact velocities in football. The objective of this research was to assess the effect of camera angle, camera distance and impact speed on the accuracy of the helmet velocity estimations. A simplified version of the full-scale game day set-up from Study 1 and 2 was used to collect video data of simulated H2G impacts that involved free fall drop tests (1.04 m = 4.52 m/s [slow]; 1.83 m = 5.99 m/s [fast]) of a helmeted anthropomorphic test device (ATD) head and neck assembly. Helmet motion was tracked using 3D motion analysis software across different combinations of stationary camera views (orthogonal, coincident, parallel, overhead) within two zones on the field. Overall, the calculated errors associated with this videogrammetry approach were comparable to prior studies in the literature that used video to quantify 3D helmet velocities in professional football games (Bailey et al., 2018; Newman et al., 2005). Interestingly, increases in camera distance and impact speed did not appreciably influence 3D video tracking accuracy in this study. However, helmet motion was mainly orthogonal to all camera perspectives, thus potential error associated with movement towards or away from the cameras was not assessed. The use of orthogonal, coincident and overhead camera angles for this videogrammetry approach was supported, as these camera pairs compared favorably to the reference velocities across all conditions (slow: 4.50 ± 0.05 m/s; fast: 6.09 ± 0.06 m/s) with relatively low errors (relative error [RE], absolute error [AE]: ≤ 3.39%; root-mean-square error [RMSE]: ≤ 0.22 m/s); although, the reported calibration and uncertainty errors favour orthogonal camera angles for the most precise 3D video tracking. Parallel camera angles demonstrated inaccuracies with horizontal measurements in-line with the camera views, which led to highest errors (RE, AE: 3.79–10.94%; RMSE: 0.18–0.55 m/s), suggesting that parallel camera angles should be avoided, where possible, when applying this videogrammetry approach in practice.

In Chapter 5, methodological considerations specific to conducting laboratory reconstructions of youth football H2G impacts were explored and elucidated, as this would represent a challenging, yet valuable, research opportunity that could be achieved using the information provided in this dissertation. Review of the limited literature on prior NFL reconstructions revealed several different approaches of varying complexity that have been used to replicate conditions of football impacts (Cournoyer & Hoshizaki, 2021; Funk et al., 2020; Jadischke et al., 2018; Karton et al., 2020; Kent et al., 2020; Newman et al., 1999; Newman et al., 2000; Pellman, Viano, Tucker, Casson, & Waeckerle, 2003). Based on these findings, an optimal approach for reconstructing H2G impact cases identified in Study 1 (Chapter 2) would likely involve: 1) a Hybrid III 5th percentile female ATD as the human surrogate; and 2) a test apparatus consisting of belt-driven sled capable of launching a partial ATD onto a field to simulate loading conditions of the “whipping” motion commonly observed with H2G impact (Bailey et al., 2018; Kent et al., 2020). The importance of the input and output parameters used in the experimental design would also have to be considered to determine the level of detail available for validating and optimizing the reconstructions.

Future Research Directions

The multi-camera video-based methodology established in this dissertation has the potential to be applied in many future research directions. This methodology offers a unique opportunity to build a detailed database of youth football helmet impact cases, similar to what has been achieved for NFL players. The video used as the basis for the descriptive and kinematic video analyses in Chapters 2 and 3 were from a convenience sample of only three youth football games. Future research efforts should therefore aim to collect further video data over the course of several seasons and across different age divisions so that cases of helmet impact leading to head injury may also be studied and compared to non-injury cases in this youth population. In addition, the versatility of this methodology for collecting and analyzing high-quality video from multiple angles lends itself for use in other settings outside of youth football games. For instance, helmet impacts occurring in practice sessions could be assessed, or other high-contact youth sports such as ice hockey and soccer. Moreover, if the limitation of full-field coverage can be resolved, then additional data on impact exposure and injury rate could be determined as well. However, despite the rich source of information that can be provided by this multi-view video data, future researchers should also carefully consider the feasibility of conducting such video analysis work from both a time and cost perspective, as this approach becomes increasingly more challenging as the number of cameras increases.

The combination of kinematic data from video- and sensor-based methods could provide a more comprehensive view of the biomechanics of real-world head impacts in sport. Previous work that has used these two methods concurrently to investigate youth football helmet impacts only employed a single-camera system (Campolettano et al., 2018), limiting the accuracy of the helmet kinematics relative to the sensor-recorded impacts. Therefore, future research should strive to utilize 3D video analysis techniques, such as the approach described in Chapter 2, to track the helmet motion of players wearing instrumented helmets or mouthguards so that both pre- and post-impact kinematics can be obtained during game play. While the limitations of these devices (Jadischke et al., 2013; Joodaki et al., 2019; Siegmund et al., 2016) and the complexity and cost of running two major data collections simultaneously would be important considerations for this research, having acceleration data that compliments the 3D helmet velocities of in-game helmet impacts would provide researchers with new information to better explore this topic.

Lastly, with increasingly more studies in the literature endeavoring to explain the underlying mechanics of head injury in youth football, the direction of future research in this area will likely follow NFL helmet impact research by performing laboratory reconstructions of real-world youth impact cases (see Chapter 5). For example, with the results from Chapter 2 showing that non-injurious H2G impacts in youth football players share similar mechanisms to H2G concussions in NFL players (i.e., "whipping" kinematic), recreating the study by Kent et al. (2020) using youth-specific impact conditions would be an interesting comparative analysis to examine the impact responses at the head and neck experienced by these players.

Conclusion

To the author’s knowledge, the collection of studies presented in this dissertation provide a novel contribution to the literature regarding the biomechanical assessment of helmet impacts in youth football. The research outlines the application and validation of a video-based methodology that used multiple cameras to acquire high-quality, multi-view video of in-game youth football helmet impacts such that detailed descriptive and 3D kinematic video analyses could be performed. Although the video-based methods used in this dissertation are time and cost intensive, the results reinforce the value of video as an effective tool for studying the biomechanics of helmet impact that occur at the youth-level and offer a research perspective that, to date, has typically been limited to televised professional football games. It is hoped that the impact of this work will continue to drive research efforts that help to mitigate head injury among these youth athletes, specifically through informing improved youth-specific helmet test standards and helmet design.

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APPENDICES

APPENDIX A – Example of the 3D video analysis procedures for helmet-to-ground impact.

Procedures

1. Review game video to identify potential on-field helmet-to-ground impact cases.
2. Determine if the impact case meets the selection criteria for quantitative analysis.
3. Extract 3-second video clips (.mp4) and image sequences (.bmp) from a minimum of two camera views that captured the impact case. Extract a calibration image (.bmp) that corresponds with each of the aforementioned camera views.
4. Review the video clip and document the descriptive parameters related to the impact case.
5. Import the synchronized image sequences and associated calibration images from the two best camera views of the impact case into ProAnalyst 3D (Xcitex Inc., Woburn, MA, USA).
6. Perform a 3D calibration procedure by selecting shared points of known dimensions between the two calibration images based on field markings (e.g., yard lines, side lines, 'hash marks', etc.) and free-standing calibration objects to set the 3D field coordinate system. Apply image processing techniques to enhance the selection of the shared points if necessary.
7. Review the image sequences frame-by-frame to identify the frame of initial helmet contact with the ground.
8. Track the 2D helmet position pre- and post-impact in each of the image sequences by manually selecting the centre of the helmet in each frame. Apply image processing techniques to improve the visual acuity of the helmet for tracking if needed.
9. Combine the two 2D tracks with the 3D field coordinate system to compute the 3D helmet motion.
10. Export the 3D positional data and calculate V_0, ΔV and Δt.

1. Review game video to identify potential on-field helmet-to-ground impact cases.
2. Determine if the impact case meets the selection criteria for quantitative analysis.
3. Extract 3-second video clips (.mp4) and image sequences (.bmp) from a minimum of two camera views that captured the impact case. Extract a calibration image (.bmp) that corresponds with each of the aforementioned camera views.
4. Review the video clip and document the descriptive parameters related to the impact case.

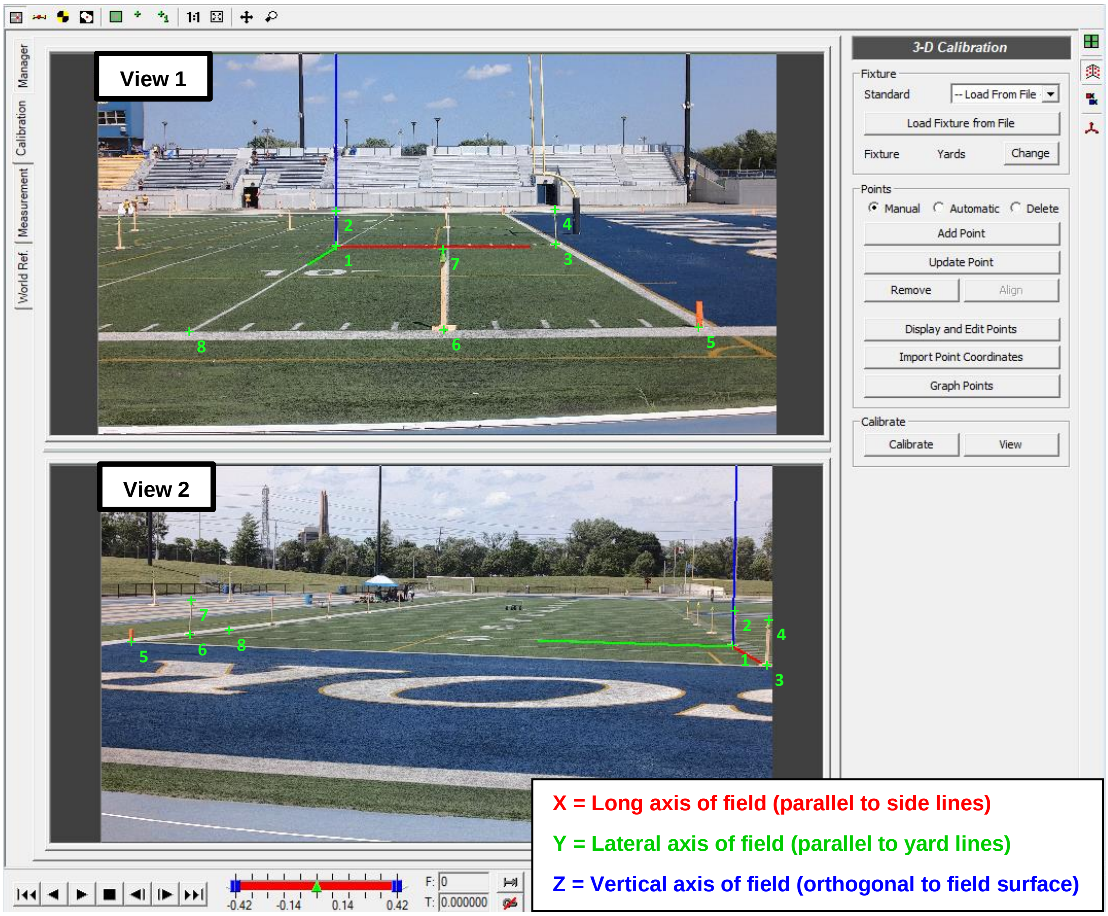
Case	Age Group	Game Time	Field Location	Play Type	Player	1st Contact	2nd Contact	3rd Contact	Impact Activity	Helmet Impact Location
20	13-to-14 years	1st quarter	7 yard line	Rush	Defense	B2B	B2G	H2G	Tackling (success)	Side

B2B **B2G** **H2G**

Description: Player tackled ball carrier on breakaway by pulling him backward to the ground. The lateral hip first contacted the ground, followed by the postero-lateral aspect of the shoulder. This induced predominantly frontal plane rotation of the head (with little sagittal plane rotation) as the side helmet impacted the ground. Incidental contact between the low back of the ball carrier and facemask occurred after helmet-to-ground contact.

5. Import the synchronized image sequences and associated calibration images from the two best camera views of the impact case into ProAnalyst 3D (Xcitex Inc., Woburn, MA, USA).

6. Perform a 3D calibration procedure by selecting shared points of known dimensions between the two calibration images based on field markings (e.g., yard lines, side lines, 'hash marks', etc.) and free-standing calibration objects to set the 3D field coordinate system. Apply image processing techniques to enhance the selection of the shared points if necessary.

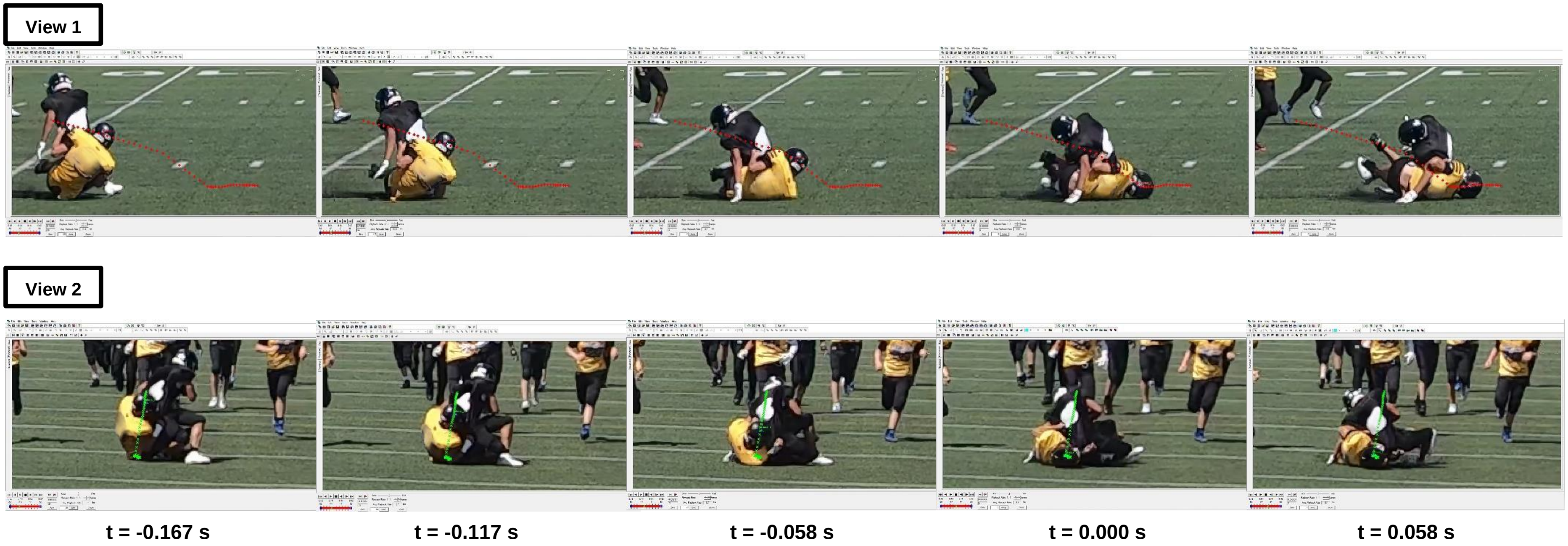


X = Long axis of field (parallel to side lines)

Y = Lateral axis of field (parallel to yard lines)

Z = Vertical axis of field (orthogonal to field surface)

7. Review the image sequences frame-by-frame to identify the frame of initial helmet contact with the ground.
8. Track the 2D helmet position pre- and post-impact in each of the image sequences by manually selecting the centre of the helmet in each frame. Apply image processing techniques to improve the visual acuity of the helmet for tracking if needed.



9. Combine the two 2D tracks with the 3D field coordinate system to compute the 3D helmet motion.
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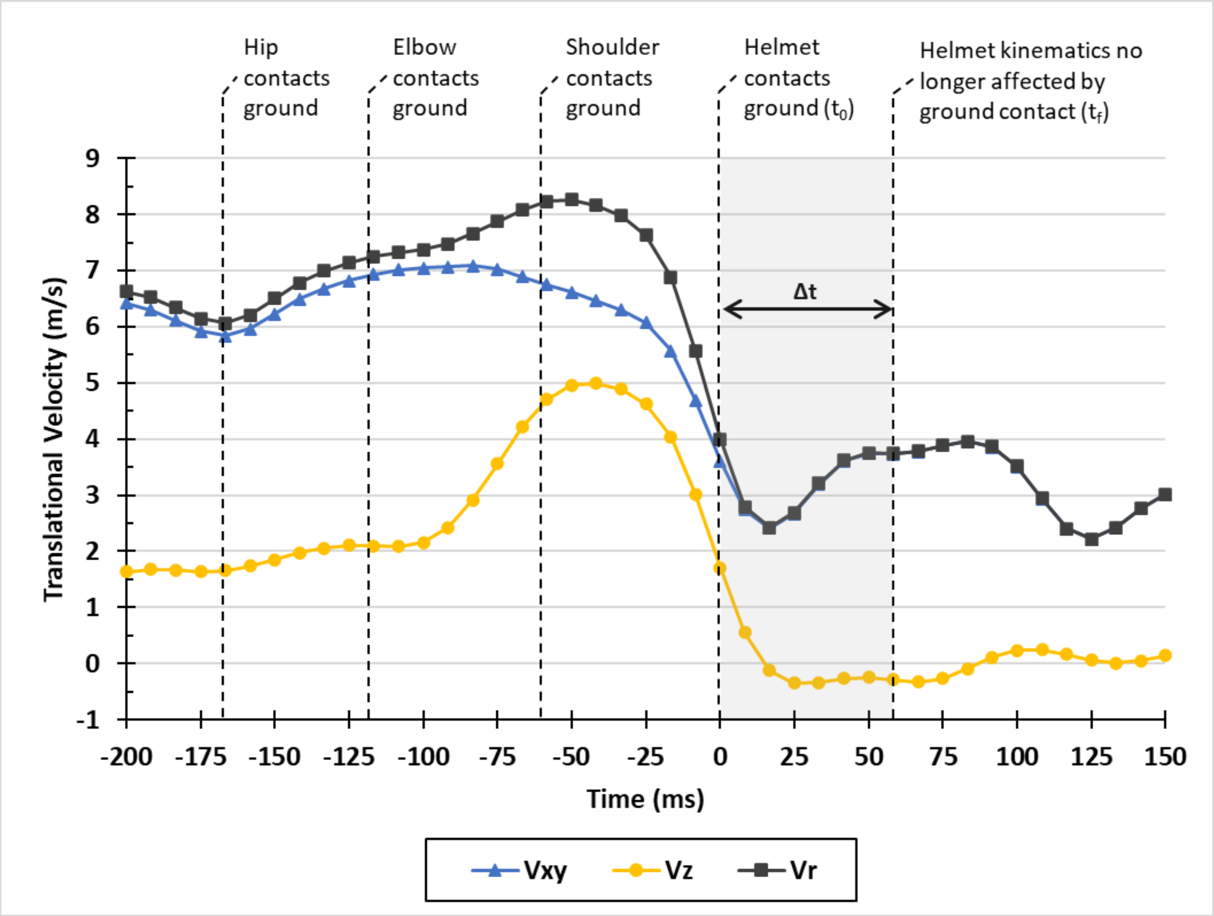


APPENDIX B – Description of camera views used for videogrammetric analysis of youth head-to-ground impacts.

Case	Impact Location (on field)	Camera		Resolution (pixels/helmet)	
		Angle	**Views**	**View 1**	**View 2**
1	S38	Orthogonal	C2, C6	1521	529
2	S44	Orthogonal	C2, C6	729	484
3	S41	Orthogonal	C2, C6	729	484
4	S37	Coincident	C1, C2	900	900
5	S13	Orthogonal	C6, C9	1089	1024
6	S13	Orthogonal	C6, C9	1024	900
7	S31	Orthogonal	C2, C6	961	576
8	S7	Orthogonal	C4, C6	1225	1681
9	S8	Orthogonal	C4, C6	900	1089
10	S42	Orthogonal	C10, C6	1024	484
11	S33	Orthogonal	C2, C6	484	529
12	S26	Orthogonal	C3, C5	1296	676
13	S26	Orthogonal	C3, C5	1296	676
14	S42	Coincident	C1, C2	1296	1225
15	S42	Coincident	C1, C2	1089	1089
16	S37	Orthogonal	C10, C7	1156	576
17	S5	Orthogonal	C4, C5	2704	900
18	S15	Orthogonal	C4, C6	625	1089
19	S11	Orthogonal	C4, C6	576	961
20	S7	Orthogonal	C8, C7	1296	1024
21	S5	Orthogonal	C8, C7	1156	1225

*Note***.** Orthogonal = a side line camera view paired with an end zone camera view; Coincident = two adjacent camera views along the same side line. The distance between the camera views and general field location of an impact event approximately ranged between 18 yards (16.5 m) and 71 yards (64.9 m).

Note: As per Bailey et al. (2018), resolution is provided in pixels per area of the helmet for each camera view.

Note. Edge of frame distortion was minimized for the video collected in this study because fixed, 50 mm lenses were used on the cameras.

APPENDIX C – Narrative description of each helmet-to-ground impact case (as per Kent et al., 2020).

Case	Narrative Description
1	Player was tripped after incidental contact with another player and fell backwards to the ground. His buttocks and outstretched arms first contact the turf, followed by the posterior aspect of his torso and finally the rear helmet. This whole-body kinematic resulted in sagittal plane rotation of the head prior to helmet impact with the ground.
2	Player was tackled and forcefully thrown to ground. During the tackle, his feet were in the air as the anterior aspect of his body approached the ground with one arm extended to arrest the impact. The facemask and chest both contacted the ground almost simultaneously.
3	Player was blocked. His body twisted axially as he was pushed toward the ground such that he fell forward. Contact of his knee and outstretched arms with the turf were unable to fully arrest his forward motion, which resulted in slight sagittal plane rotation of the head as the facemask struck the ground just prior to the anterior torso.
4	Player was tackled by multiple players. With his arms pinned against his sides throughout the tackle, his body twisted axially as he approached the ground such that the posterior aspect of his torso and rear helmet impacted the ground simultaneously. The body of the primary tackler landed on top of him, which resulted in a helmet-to-helmet contact immediately following helmet-to-ground contact.
5	Player was tackled resulting in a backwards pitching fall (similar to Case 1). His buttocks first contacted the ground followed by the posterior aspect of his torso and shoulders in rapid succession. This led to significant sagittal plane rotation of the head as the rear of the helmet impacted the ground.
6	Player wrapped up ball carrier around the torso and tackled him to the ground. As he fell sideways, the initial contact of his knee with the turf, combined with his forward motion, enhanced sagittal plane rotation of the upper body toward the ground. The lateral aspect of the shoulder and side of the helmet contacted the ground almost simultaneously.
7	Player fell backward after an attempted (i.e., failed) tackle. His body rotated axially and sagittally as he fell such that his outstretched arm and lateral hip contacted the ground before he rolled onto his back and impacted the rear of his helmet on the ground.
8	Player tripped and fell forward towards the ground. His arms extended out front of his body were unable to completely arrest his fall as the facemask contacted the ground.
9	Player tackled ball carrier and pulled him backward to the ground. His body rotated axially and sagittally as he approached the ground such that the buttocks first contacted the turf, followed by the lateral aspect of the shoulder, and then the side of the helmet with little frontal plane rotation.
10	Player (QB) was knocked down after a pass attempt resulting in a backwards pitching fall. The whole-body kinematics were similar to Case 1 and 5, wherein an outstretched arm contacted the ground, followed by the buttocks, posterior aspect of the torso and left shoulder. This contact sequence induced sagittal plane rotation of the head as the rear helmet then struck the ground.
11	Player dove forward in an attempt to catch a pass. With his arms outstretched to arrest the fall, his body axially rotated and he rolled through the initial ground contact of the postero-lateral aspect of his hip and shoulder/torso with the turf. During this time, the rear helmet struck the ground.
12	Player (QB) was tackled after a pass attempt. As he fell sideways, his knee first contacted the ground, followed by his elbow and lateral aspect of his torso/shoulder. This contact sequence induced rotation of the head in the frontal plane, which resulted in the side of the helmet impacting the ground quickly thereafter.
13	Player tackled QB during pass attempt. The whole-body kinematics were similar to Case 12, in that the player fell to his side and contacted his hip, elbow and lateral aspect of his torso/shoulder on the ground in succession. The head then rotated in the frontal plane impacting the side of the helmet on the ground.

14	Player (QB) was tackled after a pass attempt. Initial contact of his knees with the turf, combined with significant forward motion as he fell, enhanced the sagittal plane rotation of the upper body toward the ground. His body rotated axially slightly as he was unable to arrest the forward fall. The antero-lateral aspect of his torso/shoulder contacted the ground and was quickly followed by the side facemask as the head rotated in the frontal plane prior to helmet impact with the ground.
15	Player tackled QB attempting to make a pass. His feet were in the air as he fell forward toward the ground such that the lateral aspect of the torso/shoulder struck the ground just prior to the side facemask.
16	Player (QB) was knocked down after a pass attempt resulting in a backwards pitching fall. The whole-body kinematics were similar to Case 1, 5 and 10. His outstretched arms and buttocks contacted the ground first, followed by the posterior torso and shoulders. This contact sequence induced significant sagittal plane rotation of the head toward the ground, leading to a rear helmet impact.
17	Player tackled ball carrier such that his body rotated axially as he dragged him to ground. His knees initially contacted the turf before experiencing similar whole-body kinematics as observed in Case 1, 5, 10 and 16, wherein the rear helmet struck the ground after enhanced sagittal plane rotation of the head.
18	Player tackled ball carrier by pulling him backward. After the buttocks initially contacted the turf, the head and torso remained well-aligned as the body increased its sagittal rotation toward the ground. This resulted in the posterior torso and rear helmet impacting the ground almost simultaneously. The back of the ball carrier briefly contacted the facemask shortly after helmet-to-ground contact.
19	Player was tackled backward such that his lower back initially landed on top of the tackler. Similar to the whole-body kinematics of Case 18, continued rotation of the body in the sagittal plane led to almost simultaneous impact of the posterior shoulders and rear helmet on the ground. A glancing helmet-to-helmet contact from a separate tackler occurred after helmet-to-ground contact.
20	Player tackled ball carrier on breakaway by pulling him backward to the ground. The whole-body kinematics were similar to those described in Cases 12 and 13, wherein the lateral hip first contacted the ground, followed by the postero-lateral aspect of the shoulder. This induced predominantly frontal plane rotation of the head (with little sagittal plane rotation) as the side helmet impacted the ground. Incidental contact between the low back of the ball carrier and facemask occurred after helmet-to-ground contact.
21	Player on breakaway was pulled to ground. Similar to Case 19, his body initially landed on top of the tackler as he rotated sagittally backward. The body-to-body contact dampened some of the rotation as the player became momentarily airborne just prior to his posterior shoulders and rear helmet contacting the ground in quick succession.

APPENDIX D – Example of Δt and ΔV numerical verification for a 'rebound' and 'no rebound' H2G impact case.

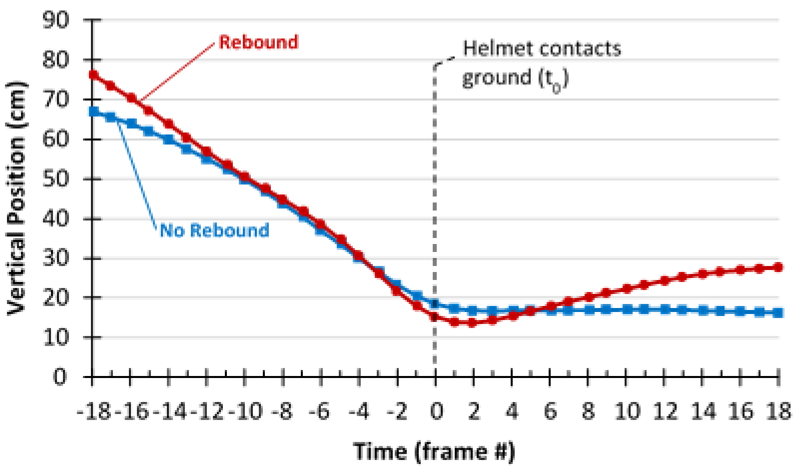
Procedures

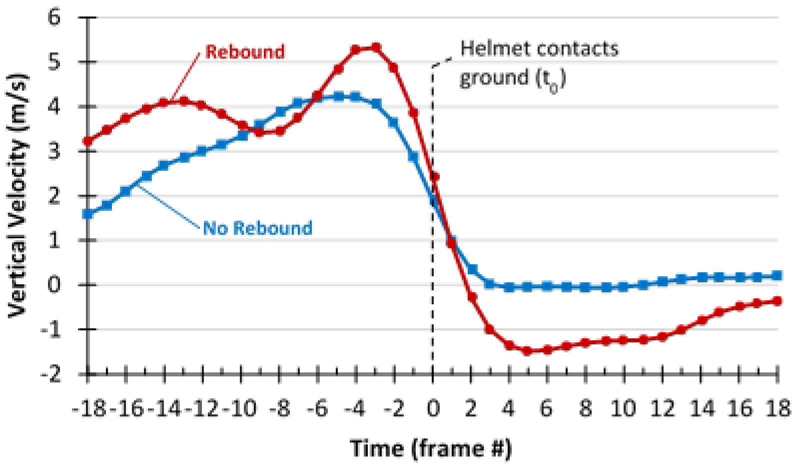
Helmet rebound cases: The frame prior to the vertical helmet position surpassing its vertical position at t_0 by > 1 mm was defined as the end of helmet contact with the ground (t_f).

No helmet rebound cases: Ground contact was no longer considered to be affecting helmet kinematics (t_f) at the time in which the rate of change of the vertical helmet velocity after impact was < 0.05 m/s (i.e., approximately constant speed).

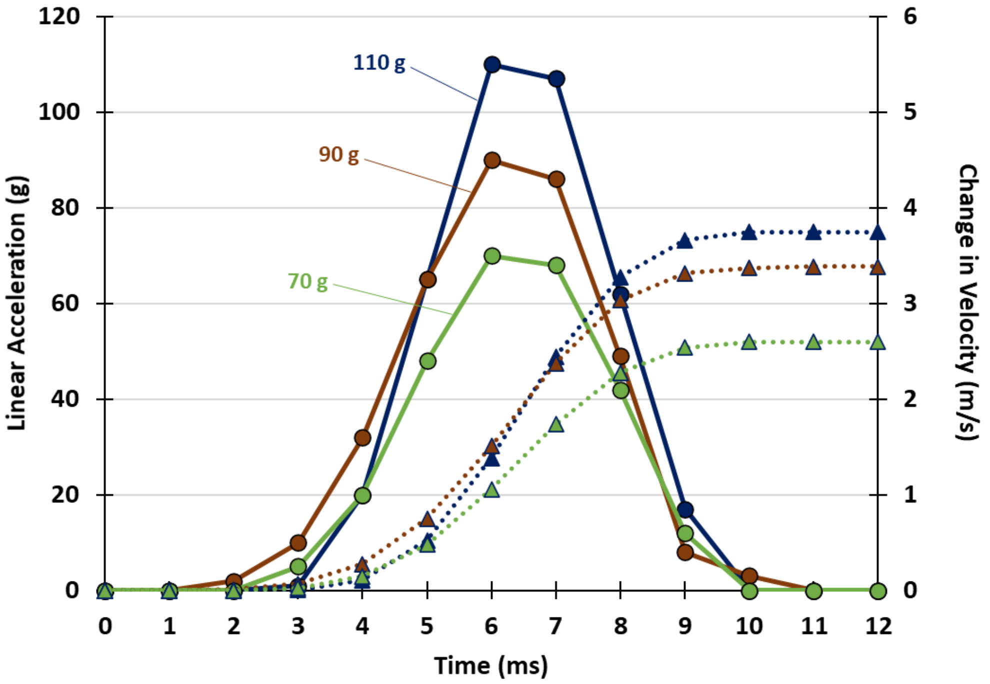
Inconclusive cases: Treated the same as no helmet rebound cases.

	Video Inspection			**Numerical Verification**		
Helmet Rebound	**t_f (frame #)**	**Δt (s)**	**ΔV**	**t_f (frame #)**	**Δt (s)**	**ΔV**
Yes	4	0.033	5.94	3	0.025	5.47
No	5	0.042	3.23	4	0.033	3.17





APPENDIX E – An adaptation of Figure 2 from Cobb et al. (2013) depicting the resultant linear acceleration and estimated change in velocity vs. time for a 110 g, 90 g, and 70 g impact recorded from 9 to 12 year old football players.



Cobb, B. R., Urban, J. E., Davenport, E. M., Rowson, S., Duma, S. M., Maldjian, J. A., Whitlow, C. T., Powers, A. K., Stitzel, J. D., 2013. Head impact exposure in youth football: Elementary school ages 9-12 years and the effect of practice structure. Annals of Biomedical Engineering. 41 (12), 2463–2473. https://doi.org/10.1007/s10439-013-0867-6

APPENDIX F – Definitions of helmet impact activity.

Tackled: Player with the ball is brought to ground by contact from opposing player; end of play.

Tackling: Player without the ball contacts player with the ball in attempt to end the play.

Tackling (success): Player without the ball contacts player with the ball and brings them to ground; end of play.

Tackling (fail): Player without the ball contacts player with the ball and does not bring them to ground; play continues.

Blocked: Player without the ball is contacted (or knocked down) by another player without the ball; play continues.

Blocking: Player without the ball contacts (or knocks down) another player without the ball; play continues.

Trip/Fall: Player with or without the ball is brought to ground in the absence of deliberate contact; play continues.

Diving/Leaping: Player with the ball makes a purposeful motion to move the ball forward (e.g., pick up first down, cross the goal line for a score) or player without the ball makes a purposeful motion towards the ball (e.g., to make a catch)

Other: Any other action not covered by the aforementioned categories.

APPENDIX G – Summary of tabulated data overall and for each age division (game A: 9-12 year age division; game B and C: 13-14 year age division).

Table G1. Frequency (%) of helmet impact cases (*n* = 95) by player position.

Player Position	**Game A**	**Game B and C**	**Overall**
Offense	14 (53.8%)	29 (42.0%)	43 (45.3%)
Defense	11 (42.3%)	28 (40.6%)	39 (41.1%)
Special Teams	1 (3.8%)	12 (17.4%)	13 (13.7%)
Total	**26**	**69**	**95**

Table G2. Frequency (%) of helmet impact cases (*n* = 95) by play type.

Play Type	**Game A**	**Game B and C**	**Overall**
Rush	25 (96.2%)	39 (56.5%)	64 (67.4%)
Pass	0 (0.0%)	18 (26.1%)	18 (18.9%)
Kickoff	1 (3.8%)	10 (14.5%)	11 (11.6%)
Punt	0 (0.0%)	2 (2.9%)	2 (2.1%)
Field Goal/Extra Point	0 (0.0%)	0 (0.0%)	0 (0.0%)
Total	**26**	**69**	**95**

Table G3. Frequency (%) of helmet impact cases (*n* = 95) by activity.

Helmet Impact Activity	**Game A**	**Game B and C**	**Overall**
Tackled	11 (42.3%)	20 (29.0%)	31 (32.6%)
Tackling	9 (34.6%)	30 (43.5%)	39 (41.1%)
*Tackling (success)**	*5 (19.2%)*	*21 (30.4%)*	*26 (27.4%)*
*Tackling (fail)**	*4 (15.4%)*	*9 (13.0%)*	*13 (13.7%)*
Blocked	2 (7.7%)	3 (4.3%)	5 (5.3%)
Blocking	1 (3.8%)	4 (5.8%)	5 (5.3%)
Trip/Fall	3 (11.5%)	0 (0.0%)	3 (3.2%)
Diving/Leaping	0 (0.0%)	3 (4.3%)	3 (3.2%)
Other	0 (0.0%)	9 (13.0%)	9 (9.5%)
*QB knockdown**	*0 (0.0%)*	*6 (8.7%)*	*6 (6.3%)*
*Trucking**	*0 (0.0%)*	*3 (4.3%)*	*3 (3.2%)*
Total	**26**	**69**	**95**

Note. Tackling was further sub-categorized into *Tackling (success)* and *Tackling (fail)*; Other was further categorized into *QB knockdown* and *Trucking*.

Note. *QB knockdown* refers to any case in which the quarterback (QB) was contacted by a defender and hit the ground after throwing the ball; *Trucking* refers to any case in which the ball carrier ran through a defender attempting to tackle them, resulting in a failed tackle.

Table G4. Frequency (%) of helmet contacts (*n* = 115) by detailed helmet contact location.

Helmet Contact Location (Detailed)	**Game A**		**Game B and C**		**Overall**	
Top	0	(0.0%)	1	(1.2%)	1	(0.9%)
Front	1	(3.4%)	8	(9.3%)	9	(7.8%)
Facemask (upper edge)	2	(6.9%)	8	(9.3%)	10	(8.7%)
Facemask (central)	6	(20.7%)	10	(11.6%)	16	(13.9%)
Facemask (side edge)	3	(10.3%)	10	(11.6%)	13	(11.3%)
Side (upper)	7	(24.1%)	25	(29.1%)	32	(27.8%)
Side (lower)	1	(3.4%)	0	(0.0%)	1	(0.9%)
Rear (upper)	9	(31.0%)	24	(27.9%)	33	(28.7%)
Rear (lower)	0	(0.0%)	0	(0.0%)	0	(0.0%)
Total	**29**		**86**		**115**	

Note. Detailed contact locations on the helmet shell and facemask were modified from Lessley et al. (2018).

Table G5. Frequency (%) of helmet contacts (*n* = 115) by general helmet contact location.

Helmet Contact Location (General)	**Game A**		**Game B and C**		**Overall**	
Top	0	(0.0%)	1	(1.2%)	1	(0.9%)
Front	9	(31.0%)	26	(30.2%)	35	(30.4%)
Side	11	(37.9%)	35	(40.7%)	46	(40.0%)
Rear	9	(31.0%)	24	(27.9%)	33	(28.7%)
Total	**29**		**86**		**115**	

Table G6. Frequency (%) of helmet contacts (*n* = 115) by helmet contact source.

Helmet Contact Source	**Game A**		**Game B and C**		**Overall**	
Helmet	4	(13.8%)	24	(27.9%)	28	(24.3%)
Ground	21	(72.4%)	47	(54.7%)	68	(59.1%)
Shoulder	1	(3.4%)	4	(4.7%)	5	(4.3%)
Arm	3	(10.3%)	3	(3.5%)	6	(5.2%)
Torso	0	(0.0%)	5	(5.8%)	5	(4.3%)
Thigh	0	(0.0%)	0	(0.0%)	0	(0.0%)
Knee	0	(0.0%)	0	(0.0%)	0	(0.0%)
Other	0	(0.0%)	3	(3.5%)	3	(2.6%)
Total	**29**		**86**		**115**	

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