Relationship between Impact Velocity and Resulting Head Accelerations during Head Impacts in Youth Football

Eamon T. Campolettano, Ryan A. Gellner, and Steven Rowson

Abstract Football helmet testing standards for youth players make use of the same testing protocol for adult helmets despite research showing differences in head impact exposure between these populations. The objective of this study was to pair estimated impact velocities with linear acceleration data collected from on-field head impacts in youth football to inform youth-specific helmet testing methods. A total of 49 youth football players received helmets instrumented with accelerometer arrays to measure head acceleration throughout the season. Using video recordings of games from a single camera, impact velocities were estimated for impacts with known acceleration magnitudes. On-field accelerations ranged from 40 to 85 g, while impact velocities ranged from 0.5 to 5.5 m/s. The average error associated with these velocity estimates was below 10%, and a zoomed-in camera view provided results more consistent with true velocity. Velocities estimated from direct helmet-to-helmet impacts matched more closely with linear acceleration than other kinds of impacts. These findings may be used to inform testing methods/conditions that are more representative of impacts experienced by youth football players.

Keywords biomechanics, concussion, linear, player tracking, rotational

I. INTRODUCTION

It is estimated that nearly 70% of the participants in football are youth players below the age of 14 [1-2]. The helmets these players must wear are certified under a safety standard established by the National Operating Committee on Standards for Athletic Equipment (NOCSAE) [3]. This standard was developed for adult football players and only considers catastrophic head injury, such as skull fracture, rather than less severe brain injuries like concussions. NOCSAE is working to implement a youth-specific football helmet testing standard, though further information is required to address how this new standard should differ from the current standard [4].

Head impact exposure research has been conducted at all levels of football and has found that increasing impact frequency and severity are observed with increasing player age (Table 1). Much of this research has centred on collegiate populations, though a growing body of literature exists for head impact exposure at the youth level. Research pairing on-field data with laboratory testing showed that the NOCSAE testing standard assesses the most severe impacts players may experience on the field, with limited performance differences between matched youth and adult football helmets [5-6].

As youth football players have a different head impact exposure profile from adult players [7-10], different anthropometry [6], and a potentially lower tolerance for concussion [11-12] further knowledge surrounding impacts at the youth level is required for the development of a youth-specific testing standard. Previous research has investigated concussive head impact speeds for professional football using video analysis as the basis for laboratory reconstructions in order to determine the linear acceleration magnitudes associated with the concussive impacts [13-15]. Pairing direct acceleration measurements with on-field impact speeds has not been done previously for a youth population and can better inform NOCSAE standards boundary conditions and test methods. By understanding the range of speeds at which youth players experience head impacts, a more representative testing methodology may be implemented. The primary objective of this study was to use a single-camera system to estimate impact velocities from youth football games and pair these data with measured linear accelerations for those same impacts. Second, the accuracy of these velocity estimates was compared against a true measure of speed to determine the error associated with the single-camera system.

E. T. Campolettano is a PhD student (Phone: +1-516-306-7210 / Email: eamonc@vt.edu). R. A. Gellner is a MS student. S. Rowson is an Assistant Professor in the Department of Biomedical Engineering and Mechanics at Virginia Tech in Blacksburg, Virginia, USA.

This methodology may be viable for estimating impact velocity in different sports.

Table 1. Youth football head impact exposure by age. As players age, they experience a greater number of impacts as well as higher magnitude head impacts [8,16,17]. Youth players received helmets equipped with helmet-mounted accelerometer arrays.

Age Group	Impacts per Season	Median Impact (g)	95% Percentile Impact (g)
7 to 8 Years[16]	161 ± 111	16 ± 2	38 ± 13
9 to 12 Years[8]	236 ± 158	19 ± 2	44 ± 8
12 to 14 Years[17]	275 ± 190	22 ± 2	54 ± 9

II. METHODS

Two teams of youth football players (average age: 12.3 ± 0.8 years; average body mass: 35.7 ± 16.2 kg) were included in this study approved by the Virginia Tech Institutional Review Board. A total of 49 players verbally assented to participation in this study while their guardians provided written consent. Each player received a Riddell Speed, Revolution, or Speed Flex helmet equipped with accelerometer arrays associated with the Head Impact Telemetry (HIT) System.

The accelerometer arrays are mounted inside the football helmets and consist of six accelerometers. The accelerometers are mounted on an elastic base so that contact is maintained with the head throughout the duration of the head impact. This ensures that head acceleration is being measured rather than helmet acceleration [18]. A 10 g resultant acceleration is used as a threshold in order to avoid the accelerometers falsely registering impacts for acceleration levels associated with tasks like running or jumping. All valid impact data were transmitted wirelessly from the helmets to a sideline computer to estimate linear and rotational resultant accelerations [19-20]. The instrumented helmets were worn for each game and practice.

Each game was filmed using a single camera collecting video at 30 frames per second in order to visually verify head impacts. Video analysis investigated game impacts that exceeded 40 g peak linear acceleration [21-22]. This study focused exclusively on those impacts that occurred during games. Practice impacts were not assessed in a similar manner, as the practice fields used by the teams in this study were not well-marked.

For the season, 336 game impacts were visually verified and resulted in a peak linear acceleration that measured greater than 40g. A subset of 50 head impacts were analysed to evaluate this single-camera system as a means of measuring impact velocity. Head impacts were selected based on several factors. Only impacts which involved helmet-to-helmet contact between two players were chosen. Impacts in which the video footage was not stationary were excluded, as a reference grid could not be developed. Lastly, impacts in which defined field markings were not present were excluded. Football fields have consistent markings of known dimensions that help to establish a reference grid. These grids are necessary in order to compute velocity estimates.

Video footage was analysed using open-source video analysis software (Kinovea 0.8.20, kinovea.org). For each impact, a perspective grid was developed using the field markings (Figure 1). The helmets of both players involved in the impact were tracked with markers over a series of video frames leading up to impact. This tracking, coupled with the dimensions of the perspective grid, allowed for determination of player displacement along the horizontal and vertical axes of the camera frame. Knowledge of the camera frame rate allowed for these displacements to be converted to average velocities for each player. The relative velocity, which was determined by taking the difference in athlete velocity along each axis, between the two athletes represented the impact velocity. The peak linear acceleration measurement and velocity estimation were recorded, in addition to classifying each impact based on whether the head-to-head impact was the first point of contact or not. Coefficients of determination were calculated to relate estimated impact velocities to peak linear head acceleration. This was done for the overall dataset, as well as the subset of direct head-to-head impacts.

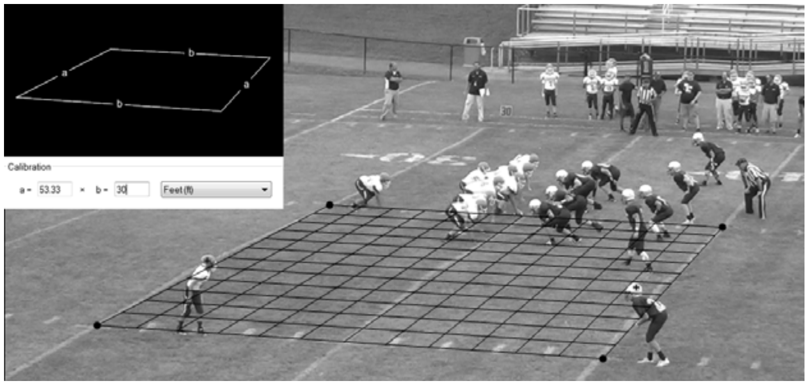

Fig. 1. Screenshot of perspective grid calibration in Kinovea software. Two-dimensional grids may be applied to video to estimate the kinematics of tracked objects (helmets). As only a single camera was used in this study, three-dimensional motion must be reconciled as changes in the two-dimensional grid space. Field markings of known dimensions must be in view for this method of velocity estimation. Objects are tracked using markers (seen on the helmets of the players in the foreground) over a series of frames to determine the object's change in position.

The velocity estimates resulting from this single camera methodology were then compared against those determined using a timing system which makes use of radio frequencies (Brower TC Timing System, Brower Timing). Two cameras recording at 30 frames per second were placed at an elevated vantage point to create as close an environment to filming a football game as possible. The two cameras were positioned at the same location with differing levels of zoom in order to determine the effect of zoom on velocity estimation (Figure 2). Running trials were conducted on different parts of the field to determine how the camera's distance from the view impacted velocity estimation (Figure 3). For all trials not at the centre of the field, subjects ran 10 yards (9.14 m) in a straight line at either full speed or a self-selected lesser speed. Trials at the centre of the field involved 10 yard runs at known angles of 30° or 45°, with subjects running both towards the camera for one trial and away from the camera in another trial. Subjects were instructed to take a running start of at least 5 yards in order to get up to speed prior to engaging the timing system. The timing system was set up at the beginning and end of the 10 yard running zone for each trial. A total of 25 trials were conducted for the various configurations outlined. The percent error between the single camera velocity estimation and the timing system velocity was computed for each trial for both the wide and zoomed views.

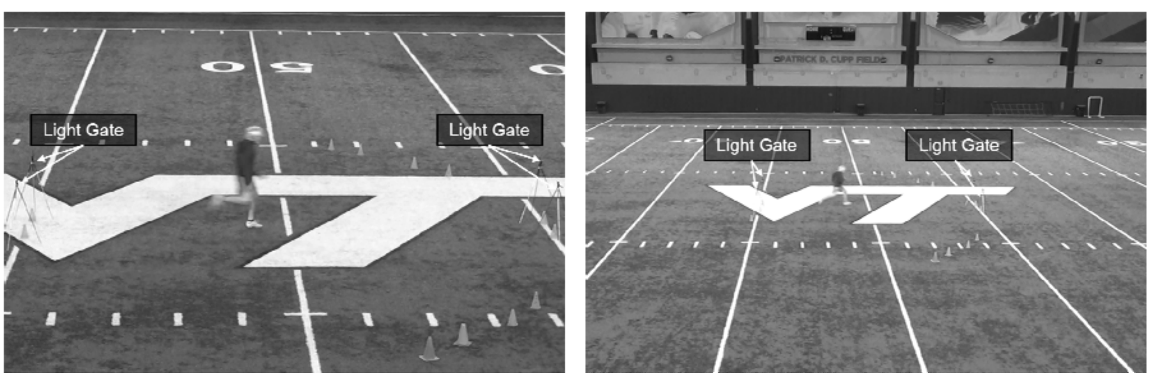

Fig. 2. Comparison of zoomed-in (left) and wide (right) camera views. The wide view provides a larger camera frame, while the zoomed-in view provides greater resolution for a given area of interest. The cameras were set-up next to each other and placed at an elevated point relative to the field to emulate filming from a press box at a stadium during a game.

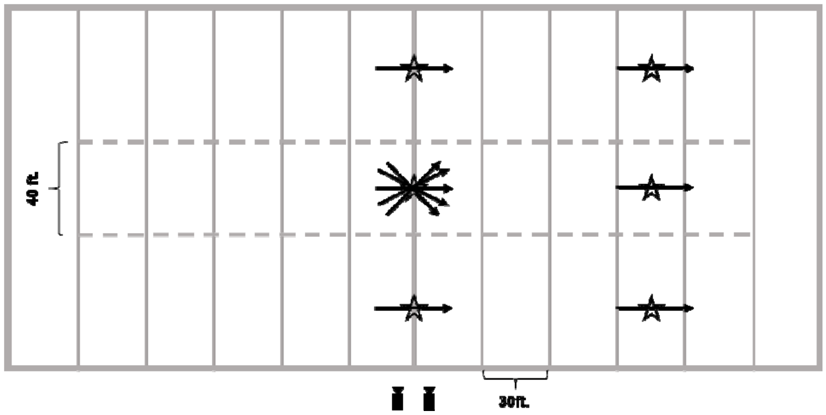

Fig. 3. Football field layout. The field is lined evenly, with distinct markings of known dimensions. Stars represent locations on the field where running trials were conducted. Black arrows represent the running paths. The two video cameras were elevated.

III. RESULTS

The head impacts included in this study ranged in peak linear acceleration from 40-85 g. These impacts represented the top 10% of all game impacts experienced by players in this study in terms of impact magnitude. Most of the impacts were between 40 and 50 g (30), with a nearly even split for impacts between 50 and 60 g (9) and those above 60 g (11). The number of impacts in which head-to-head contact was the first point of contact (27) was similar to the number of impacts in which player-to-player contact or helmet-to-shoulder contact occurred first (23). Nearly all of the head impacts above 60 g (10 of 11) had head-to-head contact first.

Individual player velocities varied from 0.2 to 5.4 m/s, while relative velocity varied from 0.5 to 5.5 m/s. In general, head impacts with higher peak linear accelerations were associated with higher impact velocities (Figure 4). Within each acceleration grouping, impact velocity varied.

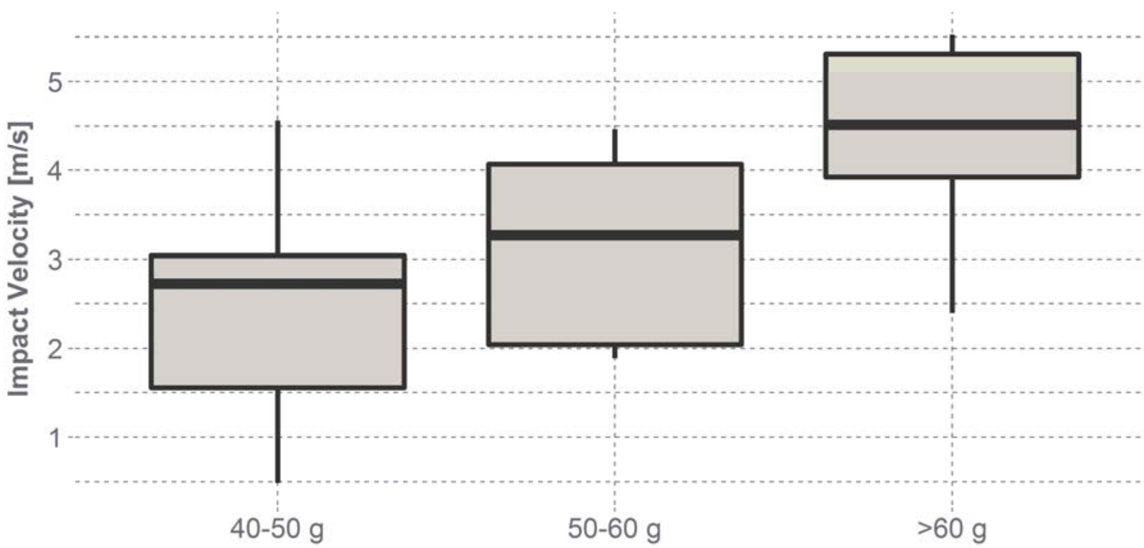

Fig. 4. Estimated impact velocity grouped by acceleration level. Increasing acceleration levels were associated with higher impact velocity.

For all impacts, only 37% of the variability in peak linear acceleration was found to be explained by impact velocity. By reducing the dataset to only the 27 head impacts in which head-to-head contact was the first point of contact, a much stronger relationship between relative velocity and peak linear acceleration ($p < 0.0001$; $R^2 = 0.726$) was observed (Figure 5). The highest impact velocity estimates were found to be associated with the highest linear acceleration measurements.

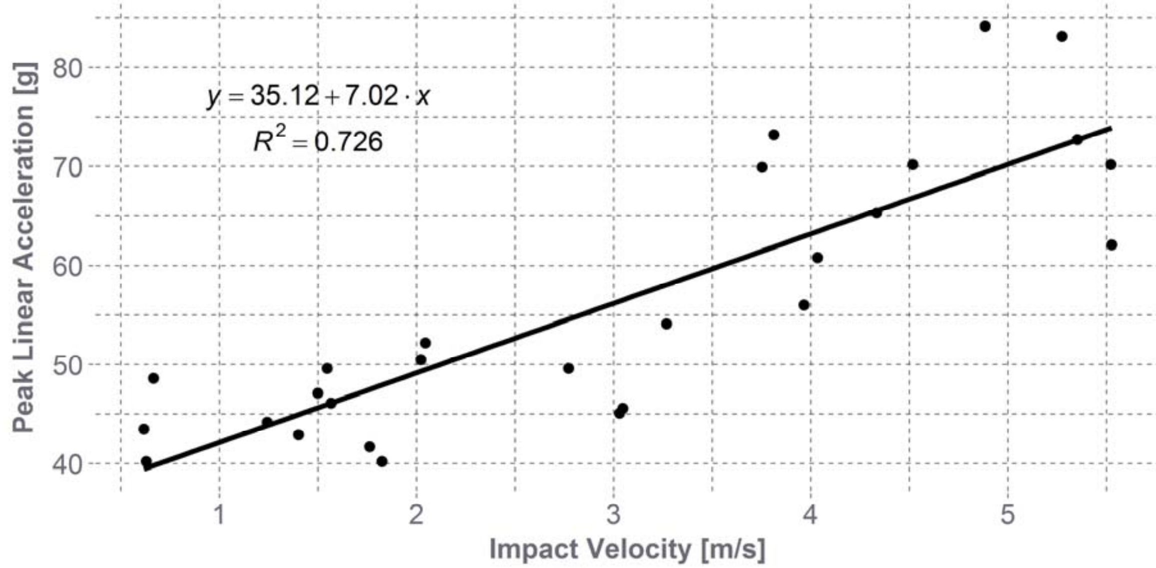

Fig. 5. Peak linear acceleration as a function of impact velocity for head-to-head impacts. Increasing impact velocity was associated with increased peak linear acceleration.

For the single-camera system employed in this study, average error was observed to be less than 10%. Average error was 8.49 ± 7.06% with the wide camera view, while the error was 5.49 ± 3.98% for the zoomed view (Figure 6). Only 19 of the 25 total trials resulted in successful tracking for velocity estimation using the wide camera view. Larger errors were observed for trials where the subject moved either towards or away from the camera.

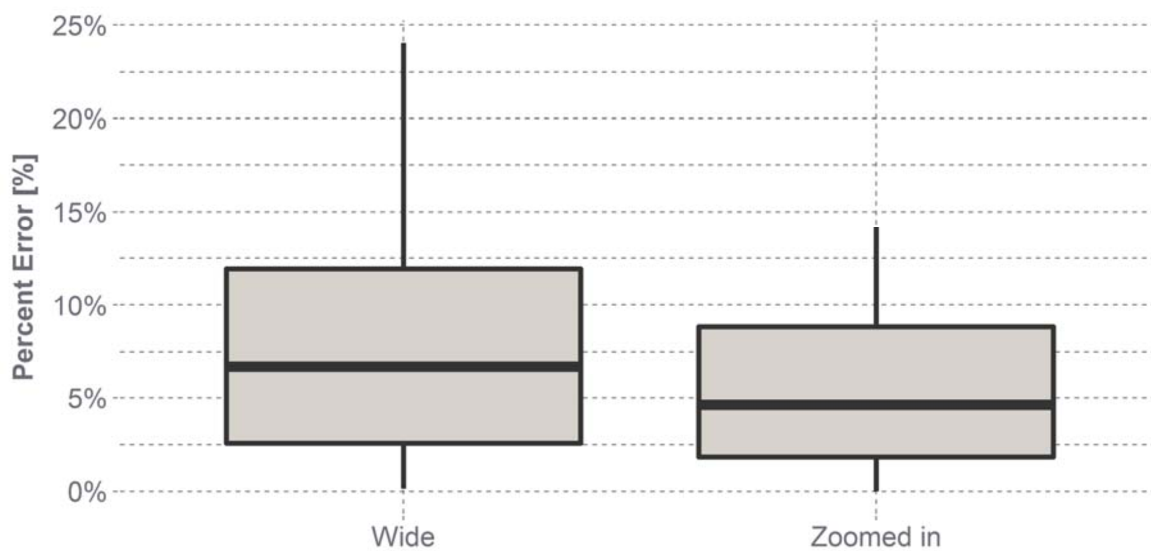

Fig. 6. Distribution of error in velocity estimation for the two camera views used in this study. Overall, errors in estimation were below 10%, with a few trials resulting in worse estimates. A zoomed-in view was associated with less error on average than a wide view.

IV. Discussion

This study paired on-field head acceleration measurements from head impact with estimated impact velocities during youth football games. The impacts represented the top 10% of all head impacts players experienced in games. It was observed that higher linear accelerations were associated with higher impact velocities (Figure 4). The most severe impacts generally occurred at higher velocities, while some impacts with lower acceleration levels resulted from high impact velocities. These impacts largely were the result of head-to-head contact not being the first point of contact. Velocity estimates tracked helmet motion for the involved players up to the point of impact. Impacts where shoulder pads collided or the shoulder pad struck the helmet first would lead to decreases in true impact velocity, which would not be reflected in the velocity estimate. These impacts would result in lower measures of linear acceleration as well.

Given the limited relationship between impact velocity and measured linear acceleration for the overall dataset, the data were classified on the basis of whether head-to-head contact served as the first point of contact. As tracking markers on the helmets served to estimate impact velocity, it follows that impacts in which head-to-head contact occurred first should yield a more consistent relationship between impact velocity and linear head acceleration. Of the 50 impacts included in this study, 27 resulted in head-to-head contact as the first point of contact. The largest acceleration measurements were observed when head-to-head contact occurred first. Velocity estimates from these head-to-head impacts were better associated with linear acceleration than for the overall dataset (Figure 5). Nearly 75% of the variability in head acceleration was explained by impact velocity for this subset. Different sources of measurement error likely contributed towards the remained of this variability and are considered as limitations of this work.

One of the head impacts assessed in this study resulted in a diagnosed concussion for the athlete. The impact was to the front of the helmet and had a linear acceleration of 70 g and a rotational acceleration of 3716 rad/s^2. This impact was the most severe linear acceleration for that player for that game. The concussed athlete was playing defensive line and was impacted by an opposing lineman shortly after play became active. The impact velocity for this impact was estimated to be 3.75 m/s. For comparison, the average concussive impact in the National Football League was found to be 9.3 ± 1.9 m/s, with linear acceleration values of 98 ± 28 g [15]. Conducting similar analysis with other known concussive impacts at the youth level would be beneficial, though a larger number of concussive data points at the youth level is necessary in order to fully characterise the biomechanics of concussion in youth football.

The accuracy of the velocity estimations from the single-camera system was assessed through experimental trials with a timing system. Previous research using Kinovea has found velocity estimation errors to be 5% [23-24]. It was observed that average error from all the trials was below 10%, with a zoomed view offering estimations closer to those measured by the timing system (Figure 6). A zoomed in view would offer greater pixel resolution for player helmets than a wide view, where individual players and their helmets are smaller relatively. This is evidenced by the fact that, for six of the 25 trials, velocity estimates could not be generated for the wide camera view due to difficulty tracking the helmet. It was also found that trials in which subjects ran at an angle either towards or away from the camera were associated with larger velocity estimate error. The video cameras are typically perpendicular to player motion, so the errors associated with in-game impacts would be expected to be on the lower end of the spectrum computed in this study.

There were some difficulties associated with tracking players during live games. As with the experimental trials, wider views led to limited tracking ability. However, the use of views that are too zoomed in also poses an issue. For impacts directly after the snap or around the line of scrimmage, this method works well. The camera must follow the game action in order to capture all potential impacts, though camera motion prevents estimation of velocity using the single-camera system. Striking the right balance represents one of the key challenges of this kind of analysis, though the use of two cameras, one with a zoomed view and the other with a wider view, would likely represent an optimal solution in order to maximise the potential to capture impact velocity for head impacts in games. In football, there are a total of 22 players on the field at one time. Tracking a single player who experienced a head impact on a given play can be complicated by the potential for other players to cross in front of the player of interest. In these scenarios, the software may lose track of the player of interest. Depending on proximity to impact, this may limit the ability to estimate velocity.

Several factors affected the relationship between impact velocity and resulting peak linear head acceleration. The HIT System has been shown to have individual head acceleration measurement errors that can be as large as 15% [25]. Impacts to the helmet facemask, which can reduce the coupling of the accelerometers and the head, are generally associated with greater error than locations on the helmet shell [26-27]. The single camera system used to estimate impact velocities was found to overpredict the true velocity, though this effect was less than 10% on average. Impact velocities were computed as average velocities, rather than instantaneous velocities. For some impacts where a player was either accelerating or decelerating during the tracking process, this may result in larger measurement errors. Impacts where head-to-head contact did not represent the first point of impact would thus be associated with higher speeds relative to the resulting linear accelerations. Different locations on football helmets may offer differing levels of impact attenuation [28-29]. For the same input velocity, an impact to the front of the helmet could result in lower levels of linear acceleration than the same impact to the side of the helmet. Lastly, there may be some error associated with the position of players' heads, as the software must reconcile player height in terms of the coordinate system setup by the reference grid rather than as a separate third dimension [23].

V. CONCLUSIONS

A methodology for estimating impact velocity from a single video camera was evaluated for youth football head impacts. On average, velocity errors associated with this system were below 10%. This single camera method will be compared against a multi-camera system in the future. These impact velocities were paired with in-helmet instrumentation measuring head acceleration during impact. Increasing head acceleration measurements were observed for increasing impact velocities, with this relationship most pronounced for direct head-to-head impacts. This combination exists for professional football, but has not been previously done at the youth level. These data have direct application for use by standards committees in developing youth-specific testing methods that are representative of real-world head impacts. The currently proposed youth football testing standard stipulates that tests are conducted at 5.2 m/s, which would be among the highest velocities observed in this study. Assessing these high severity impacts in standards testing likely represents the best opportunity to assess impacts at levels that are expected to be injurious, though verifying that 5.2 m/s laboratory impacts produce similar kinematic responses to what youth players experienced on the field is necessary in order to properly represent real-world conditions. Further, these data may also prompt manufacturers to begin to develop youth-specific football helmets.

VI. ACKNOWLEDGEMENT

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