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Head Impact Telemetry System's Video-based Impact Detection and Location Accuracy

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Abstract

Purpose: To quantify the Head Impact Telemetry (HIT) System's impact detection and location measurement accuracy using an impact biomechanics data set paired with video of high school football special teams plays.

Methods: The head impact biomechanics dataset and video were collected from 22 high school football players, wearing HIT System instrumented helmets, competing in 218 special teams plays over a single high school football season. We used two separate video analysis approaches. To quantify the impact detection accuracy, we evaluated the video for head impacts independently of the impact data collection triggers collected by the HIT System. Video observed impacts matched

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Conflict of Interest

Dr. Stitzel is a co-inventor for a mouthpiece-based head impact kinematic measurement technology that is patent pending. Riddell has previously sponsored the Matthew Gfeller Neurotrauma Symposium at the University of North Carolina at Chapel Hill (in 2017 and 2019). The remaining authors have no conflicts to disclose. The results of the present study do not constitute endorsement by ACSM. The results of the study are presented clearly, honestly, and without fabrication, or inappropriate data manipulation.

to the HIT System algorithm valid and invalid head impacts were categorized as true positives (TP), false positives (FP), false negatives (FN), and true negatives (TN). To quantify impact location accuracy, we analyzed video-synchronized head impacts for impact location independent of the HIT System's impact location measurement and quantified the estimated percent agreement of impact location between the HIT System recorded impact location and the impact location observed on video.

Results: The HIT System's impact filtering algorithm had 69% sensitivity, 72% specificity, and 70% accuracy in categorizing true and non-head impact data collection triggers. The HIT System agreed with video observed impact locations on 64% of the 129 impacts we analyzed (unweighted k = 0.43, 95% CI: 0.31 – 0.54).

Conclusion: This work provides data on the HIT System's impact detection and location accuracy during high school football special teams plays using game video analysis that has not been previously published. Based on our data, we believe the HIT system is useful for estimating population based impact location distributions for special teams plays.

Keywords

head injuries; concussion; American football; injury prevention; head impacts

INTRODUCTION

High school athletes represent one of the largest athletic cohorts in the United States, with almost 8 million student-athletes participating annually.(1) Concussions account for 15% of all sport-related injuries sustained by high school athletes.(2) Compounding this injury prevalence, recent studies suggest participating in collision sports lead to cumulative head impact exposure that may result in long-term sequelae,(3) and brain changes in as short as one season.(4,5) These reasons make it significant and worth studying this population's health and safety. High school football has over 1.1 million participants annually and high concussion incidence rates, ranging from 4.7 to 9.4 concussions per 10,000 athletic exposures over the last 15 years.(1,6–8) Football's high collision environment exposes players to frequent head impacts and thus a risk for concussions across youth, high school, college, and professional populations.(6,9,10) Player-to-player contact is the primary concussion injury mechanism.(6,7,11) Reducing or eliminating contact during practices and ensuring proper football tackling and blocking techniques are methods that may reduce concussion risk in youth and high school football populations.(6,7,12) Modifying existing rules or introducing new rules limiting the potential for player collisions and other high energy contact is another method that may lower concussion incidence, especially during competition.(13,14)

Special teams plays (i.e., kickoffs and punts) commonly lead to high energy player collisions due to the large closing distances between opposing players on the field.(15) Kickoff/kickoff return and punt/punt return plays account for 10–20% of concussions in professional and high school football,(16–18) and, on a play by play basis, special teams plays present a 1.7 to 4.3 times higher concussion risk compared to injuries during run and pass plays in professional football.(16,17) As a result, kickoffs were moved from the 30- to the 35-yard line in professional football beginning in 2011, which increased the number of touchbacks in professional football by 32% and reduced the likelihood of players sustaining potential concussions on kickoffs.(19) This rule modification was supported by data from helmet-based accelerometers in collegiate football that showed collisions occurring over long closing distances were the most severe.(15)

The Head Impact Telemetry (HIT) System is the most commonly used head impact sensor in football. As noted above, this system has been used to inform rule changes at the professional level.(15) However, the effectiveness of these data-derived rule modifications hinges on the sensor's accuracy in measuring the head impact biomechanics. In general, accurate head impact magnitude and location data from head impact sensor measurements require that the sensor (1) has sufficient bandwidth and amplitude range to measure the loading environment,(20) (2) couples securely to the head to reduce measurement error from head-sensor relative movement,(21) and (3) uses some software algorithm to retain true head impacts and remove data collection trigger events not related to a head impact.(22,23)

In laboratory testing using anthropometric test device (ATD) headforms, the HIT System had variable performance in measuring the impact location of impacts directed to the helmet facemask and crown.(24,25) The HIT System recorded those impacts as back of the helmet instead of what should have been the correct impact location of front or top.(24,25) However, the HIT System may measure facemask and crown loading differently when on a human head (rather than an ATD) due to head shape and head-helmet coefficient of friction differences between a human head and an ATD.(26,27) In addition, laboratory evaluations using the football HIT System demonstrated that between 4% to 25% of data can be missed due to data collection trigger failures or incorrect removal of data by the filtering algorithm.(24,28,29) The HIT System's impact filtering algorithm accuracy has not been quantified in an on-field setting and may be examined using video analysis.

It is important to have accurate impact data to understand head injury mechanisms in terms of impact frequency, magnitude and directional loading to create or modify data derived rules for player safety. The purpose of this study was two-fold. We first aimed to quantify the HIT System's head impact filtering algorithm accuracy in an on-field environment during high school football special teams plays. We used video synchronized with HIT System data to estimate the true positive, false positive, false negative, and true negative rates for impacts collected during special teams plays and processed with the HIT System's impact filtering algorithm. We then aimed to quantify agreement in impact location between a video reviewer and the HIT System. This study examined the HIT System's performance in actual practice and game settings (rather than laboratory settings). However, video review is not without error even by a trained observer. Thus, we believe these true positive, false positive, false negative, and true negative rates, and location agreement statistics, are best interpreted as estimates informed by quantifying and reporting intra- and inter-rater agreements for impact detection and location. We hypothesized that video estimates of impact detection and location would not perfectly agree with measurements made by the HIT System. Because this study used video analysis as a proxy gold standard, we limited all analyses to special teams plays only. As noted above, special teams plays represent a football play type with high concussion risk. From a pragmatic standpoint, special team plays are more likely to be open field plays and are therefore more amenable to video analysis.

METHODS

Participants and Data Collection Procedures

The head impact biomechanics data used in this study were collected during the 2017 season from a single high school football team. Eligible participants for the study wore either a Riddell Revolution, Speed, or Speed Flex helmet to accommodate a HIT System encoder and were members of the high school football team. The study was approved by our institution's Office of Human Research Ethics. Athlete consent and parental assent were required prior to study enrolment. Enrolled participants' helmets were instrumented with a HIT System encoder prior to the beginning of the competitive season. An athletic trainer at the school or a research assistant initiated the HIT System for data collection for all practices and games for the 2017 season.

The head impact biomechanics data collected by the HIT System comprised of both valid and invalid impacts per HIT System's impact filtering algorithm. Six accelerometers within the HIT System encoder continuously sampled during a game until one of the accelerometer channels exceeded a 14.4 g acceleration threshold. Data were collected for 40 ms at 1 kHz and transmitted to a sideline computer where a proprietary algorithm determined the head impact kinematics, impact location, and impact algorithm validity.(30–32) Impact location category was determined according to the impact's azimuth and elevation coordinates (Figure 1). The HIT System's algorithm determined impact validity using two criteria. First, data collection for a single impact event commenced when one of the six accelerometers exceeded a threshold of 14.4 g. Once triggered, data from all six accelerometers were collected and processed through a proprietary algorithm to compute the resultant linear acceleration. This resultant linear acceleration may ultimately be a value lower than the single-axis trigger threshold. Thus, only impacts for which the resultant linear acceleration exceeded 10 g were retained for our analyses. These values are consistent with studies employing the HIT System and reduce the risk of impacts less than 10 g (associated with running or jumping movements) from being misclassified as head impacts.(32–34) The second criterion required that the acceleration pulse for a data collection trigger had characteristics of an impact to a helmeted head based on rigid body dynamics.(31,32) The second criterion's intended purpose removed data collection trigger events where the helmet was not on the head. Once the algorithm determined that a trigger event satisfied these two criteria, it was available in real-time on the sideline computer and later via the HIT System's cloud-based web portal (the Redzone Suite). Algorithm invalid impacts were stored locally on the sideline data collection laptop in LinkStatus Log files. Each data collection trigger event, within the LinkStatus Log File, contained a date/time stamp for the trigger event and an identification number associated with that player's specific sensor. The presence of a data collection trigger event date/time stamp within the LinkStatus Log file that did not appear in the dataset downloaded from the Redzone Suite indicated that these data were deemed invalid per the HIT System's algorithm validity criteria.

Our research team filmed all the games for the high school football team participating in the study. We used a single video camera (Canon VIXIA HF M30 or R100 video camera; Canon Inc., Tokyo, Japan) positioned as close to the 50-yard line as possible and at the highest available vantage point. We recorded high definition film from this location. There was natural deviation in camera placement from one venue to the next, but the positioning remained consistent at the venues we collected these data. Games were recorded at 60i (60 interlaced fields per second) with a tight angle allowing for better resolution of the head impacts player's sustained during competition. Our research team filmed all games with a continuous feed to easily synchronize the film with the HIT System impact data according to the procedure outlined by the National Institute of Neurological Disorders and Stroke common data elements for video confirmation of biomechanical devices used in traumatic brain injury research.(35) All research team members responsible for filming games underwent training prior to the team's first game. Our team members have collected video across multiple years and this experience was leveraged to obtain consistent game film quality. Only video for special teams plays for the instrumented high school football team in the 2017 season were evaluated for this study.

Video Review

A single reviewer analyzed on-field special teams video data using VLC media player (version 2.2.8) independent of the data generated by the HIT System including the head impact kinematics, location, and algorithm validity data. Our video reviewer for this study (KRC) had ten years of football playing experience with an additional four years of reviewing impacts captured by video and the HIT System. We used video assessment questionnaires similar to previous studies.(15,36,37) Separate analyses were used for evaluating the HIT System's head impact filtering algorithm to detect impacts (Aim 1) and impact location accuracy (Aim 2). Both video review analyses were completed for all special teams plays over 12 games in the 2017 season.

Impact detection—We first used the video-assessment to examine whether or not an impact occurred as the proxy gold standard with the goal of estimating the HIT system's impact detection accuracy. The video reviewer watched each instrumented player through an entire special teams play and documented camera times when an instrumented player sustained an impact capable of triggering HIT System data collection.(38) The reviewer recorded camera times when the instrumented player was no longer in view of the camera and the duration they were out of view. Video reviewed impacts had to meet all inclusion criteria outlined in Table 1. The video reviewer logged camera times of video observed head impacts to a data collection form for merging video analysis data with HIT System valid and invalid data collection impact trigger events. Only impact trigger events that satisfied all inclusion criteria were merged with HIT System data (Table 1).

Impact Location Agreement—To estimate the HIT system's impact location accuracy, we were limited to the universe of head impact events recorded by the HIT System.(15,36,37) The video reviewer entered synchronized video-data collection trigger event camera times into VLC's Jump to Previous extension application for video analysis. Impacts analyzed with this approach had to meet all the inclusion criteria outlined in Table 2 before the reviewer categorized the video observed impact location according to the HIT System's impact location definition (Figure 1). Video analysis data were paired with the head impact biomechanics data using a unique impact identification number. Only impact trigger events that satisfied all inclusion criteria were merged with HIT System data (Table 2).

Our protocol used an expert adjudication process to determine impact location based on the video. Our video reviewer with the football playing and video evaluation experience (KRC) identified 130 impacts that met all inclusion criteria outlined in Table 2 from head impact events recorded by the HIT System. A second reviewer then analyzed the same 130 impacts for only impact location (JSB). A third video reviewer (AJB) then analyzed impacts where the two initial video reviewers disagreed (n = 11). We reached a video observed impact location consensus for an impact when at least two reviewers agreed on the location. For one of the 130 impacts, all three reviewers disagreed on the impact location, and we removed this impact from the final dataset for statistical analysis because of this ambiguity in assessing this impact's location from video.

Inter- and Intra-Reliability Assessment

As noted above, video review of on-field play has some degree of error. To quantify the reliability of video review for our primary purpose, the reviewer watched and reviewed a single football game twice to establish intrarater reliability for documenting impacts. The first and second video review sessions were separated 30 days apart. The video reviewer replicated 92% of the data collection trigger and non-trigger events between the two video review sessions and reliably applied the inclusion criteria to head impact events for later merging with HIT System data (Table 1).(36,37,39)

For the location assessment addressing our second aim (limited to the impacts recoded by the HIT system), our video reviewer watched and reviewed 60 impact data collection trigger events to establish their intrarater reliability. These 60 impacts came from multiple games evenly distributed across the four special teams play types and were reviewed on two sessions separated by 30 days. We determined our video reviewer's reliability on applying the inclusion criteria to the 60-impact data set, and reliability on analyzing the video observed impact location for impacts meeting all inclusion criteria (Table 2). The video reviewer reliably applied the inclusion criteria to the 60-impact data set (Table 2) and demonstrated a 90% agreement between the two sessions on documenting the HIT System impact location [unweighted Kappa (k) statistic = 0.82].(36,37,39)

We also assessed interrater reliability using similar methods. An additional video reviewer analyzed the same 60-impact data set for inclusion criteria and video observed head impact location. The interrater percent agreements and kappa statistics were less than the intrarater percent agreements and kappa statistics (Table 2). The two raters demonstrated moderate agreement (73%) on categorizing impact locations observed in the 60-impact data set (unweighted $k = 0.52$).(39)

Data Reduction & Statistical Analyses

Head impacts observed on video that were documented with the video as a gold standard proxy and impacts measured by the HIT System were categorized according to the definitions in Table 3. In addition to estimating the true positive, false positive, false negative, and true negative rates, we estimated the HIT System's impact algorithm filter's sensitivity, specificity, positive predictive value, and accuracy during special teams plays with the equations 1–4 below:

$$\text{Estimated Sensitivity} = \frac{\text{TP}}{\text{TP+FN}} \tag{1}$$

$$\text{Estimated Specificity} = \frac{\text{TN}}{\text{TN+FP}} \tag{2}$$

$$\text{Estimated Positive Predictive Vale} = \frac{\text{TP}}{\text{TP+FP}} \tag{3}$$

$$\text{Estimated Accuracy} = \frac{\text{TP+TN}}{\text{TP+FP} + \text{FN} + \text{TN}} \tag{4}$$

where TP is the number of true positives, FN is the number of false negatives, FP is the number of false positives, and TN is the number of true negatives.

For impact location agreement, we calculated the percent agreement and used an unweighted Kappa agreement analysis to determine the head impact location agreement between a video reviewer and the HIT System.(39,40) An unweighted Kappa statistic of one indicated perfect agreement between the video observer and the HIT System. An a priori sample size estimation was considered for this project. We required 88 impacts meeting our inclusion criteria to have 80% power that an obtained HIT System impact detection sensitivity of 95% is different from an ideal sensitivity of 99%. All other analyses were sufficiently powered based on our estimate for powering HIT System impact detection sensitivity. We carried out our statistical analyses in SAS (Version 9.4, SAS Institute Inc.), and set an a priori alpha level of 0.05.

RESULTS

There were 646 impact data collection trigger events from the HIT System with 371 impact data collection trigger events classified as valid by the HIT System's impact filtering algorithm. These impact trigger events were collected from 22 players participating in 218 special teams plays (58 kickoff cover plays, 54 kickoff return plays, 50 punt cover plays, and 56 punt return plays).

Impact Detection Rate

A total of 1500 player-plays were reviewed, and we determined 495 impacts occurring on video. Of the 495 impacts we identified on video, 316 matched with an impact trigger event from the 646 HIT System impact data collection trigger event data set. Therefore, 330 HIT System impact trigger events had no corresponding impact observed on video. The 646 HIT System impact trigger events that had the matched video observed impacts (n = 316) and

HIT System trigger events with no video observed matched impacts (n = 330) were reduced to 317 trigger events after applying the inclusion criteria from Table 1.

The 317 trigger events were categorized according to Table 3 and are presented. An estimated 70% of the 317 impact trigger events were accurately classified as true head impacts and non-head impacts by the HIT System's impact filtering algorithm. A larger proportion of estimated false negatives occurred among trigger events incorrectly classified by the HIT System's impact filtering algorithm. The HIT System impact filtering algorithm had an estimated 69% sensitivity in detecting true head impacts observed on the video, and an estimated 72% specificity in classifying non-head impact motions observed on video as non-head impact events. Finally, an estimated 88% positive predictive value indicated the likelihood that an impact classified as true head impact by HIT System's impact filtering algorithm was actually a true head impact observed on video.

Impact Location Agreement

Of the 646 impact trigger events that occurred on special teams plays, our video reviewer identified 198 impact trigger events that met all inclusion criteria for further quantifying video observer impact locations (Table 2). Of the 198 included impact trigger events, 130 were classified as valid by the HIT System's impact filtering algorithm and provided impact kinematic and location information. The video from these 130 impacts underwent review by two video reviewers for determining a video observed impact location with 129 used for statistical analysis.

The impact location measured by the HIT System agreed with our impact location observed from video on 82 of the 129 (64%) reviewed impacts. The HIT System location data and our video observed impact location data had weak agreement according to the unweighted kappa agreement statistic suggesting that 15% to 35% of the impact locations measured by the HIT System and determined by a video observer were reliable (unweighted $k = 0.43$, 95% confidence interval: 0.31 – 0.54). Most of the disagreements on impact location between the HIT System and the video observed impact location differed by one location category (Figure 2). However, four impacts observed on video occurring to the front of the head were recorded as back by the HIT System, two impacts occurring to the back of the head on video were recorded as impacts to the front of the head by the HIT system, and one impact was observed occurring to the right of the head on video but the HIT System recorded it as a left impact.

DISCUSSION

This is the first investigation to report on the HIT System's impact detection rate for special teams plays. The HIT System's impact filtering algorithm accurately categorized 70% of the video-observed head impacts as head impacts. Importantly, 23% of the video observed impacts were categorized as non-head impact events by the HIT System filtering algorithm. It is important to note our results apply to special teams plays, a phase of play with high risk of concussion that is more amenable to video analysis than other football phases at the high school level. These results indicate that studies using the HIT System as a head impact data collection system could underestimate head impact frequency during special teams plays, and possibly other play types.

This is also the first study to attempt to estimate the HIT System's impact location measurement accuracy. Almost 95% of the impact locations observed on video and measured by the HIT System either agreed on the exact or adjacent impact location region. However, caution is warranted in interpreting this result, since the regions are large. Only 52% of impacts disagreeing on impact location between the video observer and the HIT System occurred within ± 22.5° of azimuth of an impact location category boundary or within 25° of elevation along the top location category boundary.

In this study, the HIT System impact filtering algorithm's estimated sensitivity, specificity, positive predictive value, and accuracy were less than those reported for a mouthguard system used in college football players.(22) These differences could be attributed to our study only describing algorithm performance for special teams plays where the loading environment has a wide range, due to the short and long closing distances experienced across the different special teams play types.(15,37) From a technical standpoint, the mouthguard system used an infrared sensor within the mouthguard to automatically remove non-head impact triggers when the mouthguard was not on the teeth.(22) Additionally, the mouthguard system used a machine learning program to classify true and non-head impact events. The program used power spectrum densities and wavelet transform features from the linear acceleration and angular velocity data collected from impacts delivered to collegiate football players while wearing the mouthguard.(22) These spectral and wavelet transformations showed that true impact events had higher amplitudes at lower frequencies, while non-impact events had amplitudes and oscillations at higher frequencies.(22) While using linear acceleration thresholds does not sufficiently discriminate between true head impact and non-impact events,(23,41,42) the frequency content within the measured kinematic signals holds promise for classifying true head impacts.(22)

There were 73 impacts observed on video that were categorized as non-head impact events according to the HIT System impact filtering algorithm (Table 3). This is a higher estimated false negative rate in football than documented false negative rates in soccer on evaluations using the X2 Biosystems xPatch.(23) There are clear differences in the hardware configurations (six single axis linear accelerometers in the HIT System vs. tri-axial linear accelerometer and gyroscope in the xPatch), head coupling methods (in-helmet with the HIT System vs. head based with the xPatch), impact filtering algorithms, and loading environments (special teams high school football for the HIT System vs. collegiate soccer for the xPatch) that could reasonably explain differences in false negative rates. The studies also differed on the approach for cross-referencing impact triggers with video. We evaluated the video for head impacts independently of the HIT System trigger events.(38) This meant that when we tracked a player on a special teams play, we had no prior knowledge that the HIT System triggered for data collection. Other approaches used synchronized date-time stamps from the head impact sensor and video to jump to points in the video when the head impact sensor triggered for data collection.(23,41,42) Our approach removed potential bias from the video observer for determining if a true impact had occurred on video or not during the review process.

Our data indicate that the HIT System and a video observer moderately agreed on determining impact location.(39) One reason for the disagreement on impact location between a video observer and the HIT system is the acknowledged subjectivity of observing impact locations on video. This is a limitation of any video review study. The HIT System determined a quantitative impact location category based on the azimuth and elevation coordinates calculated from impact acceleration (Figure 1). Our video observer used landmarks on the helmet from Figure 1 to determine a qualitative impact location category. Therefore, some error level could exist on determining the impact location through video observations. However, impacts included in the location agreement analysis between the HIT System and the video observed impact location met strict inclusion criteria. These criteria included 1) unobstructed impact views, 2) observed head contact to the instrumented player, and 3) observed head impact locations that could be clearly categorized by a HIT System location. Oblique impacts directed to the boundary between two or more impact location categories were excluded to avoid increasing the chance for disagreement between the HIT System and the video observed impact location on a difficult area to judge. With these strict criteria, 130 impacts were considered for impact location statistical analysis, and at least two separate video reviewers independently agreed on 129 out of the 130 impact locations observed on video. It is possible these stringent inclusion criteria may lead to selection bias influencing the study results reported. However, we believe our approach ideally decreased the subjectivity associated with categorizing impact locations according to video and allowing for stronger interpretations of our results.

The HIT System determined that 85% of the impacts were to the front and side locations, and our video observer determined a similar percentage with almost 90% of the impacts directed onto the front and side locations. A previous study showed similar impact location distributions determined from video-based methods and head impact sensor methods.(38) The HIT system could be useful for estimating population based impact location distributions for special teams plays where many impacts, on the order of thousands, are collected. Impact location for rarer outcomes, such as the impact location distribution for injurious impacts, should be corroborated with video analysis by multiple video reviewers when feasible.

Limitations

The results of our investigation must be framed within its methodological limitations. First, we used a single camera view to analyze potential head impacts and head impact location through video analysis. An additional camera set up in the endzone would have allowed for better impact and impact location identification for collisions where players were moving sideline-to-sideline.(22,38) A single camera view has been used in other studies that paired head impact biomechanics with video, and a camera set up on the sideline is the preferred angle because most of the player movement in football is endzone-to-endzone.(36,37) Documenting head impacts and head impact location from video, independent of the impacts measured by the HIT System is subjective. We used strict inclusion criteria and impact definitions in order to conservatively assess video observed impacts and impact locations. This may have resulted in an inadvertent selection bias influencing our study results. Our video reviewer had over 10 years of football playing experience (4 at the college level) and over four years of video-based impact analysis. He also conservatively applied inclusion criteria to observed impacts and impact locations to develop the data sets for statistical analysis. Fewer impacts passed the inclusion criteria for the location analysis (33/60) for our experienced video reviewer as compared to a second video reviewer who passed more impacts for the location analysis (45/60) based on the inclusion criteria during our interrater reliability assessments. Additionally, multiple reviewers assessed our conservatively identified head impact dataset of 130 impacts for impact location, and at least two reviewers independently agreed on 99% of the head impact locations observed on video. This provided further confidence that our video observed impact locations used in our agreement analysis with the HIT System's impact location measurements were less subjective. Importantly, our results currently apply to special teams plays in high school football only. Previous research shows that the average impact magnitudes differ between special teams and run or pass plays, and at different levels of the sport.(15,37) Future research is needed to estimate the HIT System's impact filtering algorithm and location measurement accuracy on run and pass plays and in professional, collegiate, and youth settings. Our study was limited to a single high school football team; this may impact our study's generalizability.

Conclusion

This study provides valuable data on the performance of the HIT System's impact filtering algorithm and location measurement accuracy for special teams plays in high school football. We estimate that the HIT System's impact filtering algorithm correctly categorized 222 (70%) of 317 impacts as true data collection trigger events, relative to video analysis of special teams high school football plays. Furthermore, a high proportion (23%) of the head impacts observed on video were categorized as non-head impact events by the HIT System's impact filtering algorithm. We caution that video review is a proxy gold standard and has error, therefore, we believe these findings should be treated with caution. From a research perspective, there is need for impacts and impact locations to be accurately measured in order to quantify the impact loading environment for teaching athletes proper concussion prevention techniques and making data-informed rule changes aimed at reducing concussion risk.

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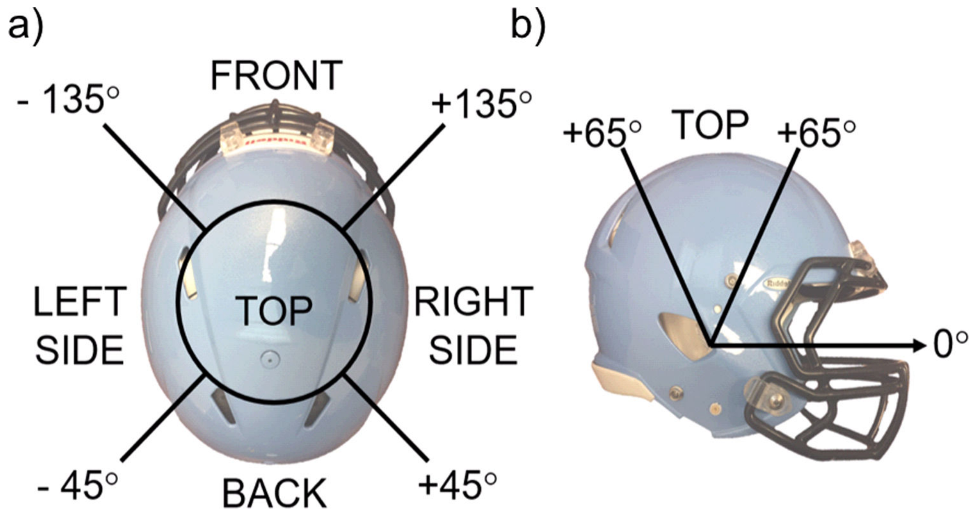

Figure 1:

The HIT System calculated head impact location in azimuth degrees around the head (a), in elevation degrees (b), and as an impact category. Impacts > 65° elevation are classified as Top impacts regardless of the azimuth degree calculation. Otherwise, impact location category was determined by the azimuth degree falling into one of the 4 location bins (Front, Right Side, Left Side, and Back).

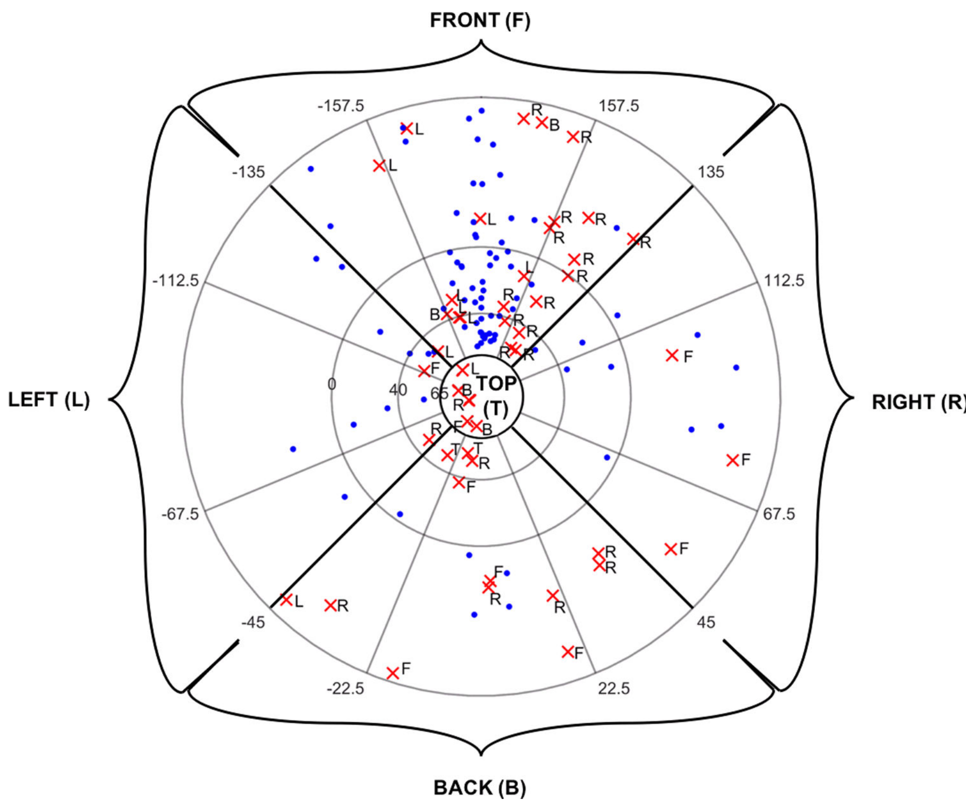

Figure 2:
Summary of agreed and disagreed impact locations. Azimuth (numbers around figure) and elevation (numbers inside figure) coordinates for impacts where the Head Impact Telemetry (HIT) System and the video observed impact location agreed (blue dots), and disagreed (red crosses). Impact location categories at the edge of the figure describe the impact location assigned by the HIT System. Impact location for video observed impact location is shown next to the point for the disagreements.

Table 1.

Inclusion criteria used to determine if a potential head impact trigger occurred while watching video for the video gold standard proxy analysis. Intrarater agreements on determining potential impact trigger events and inclusion criteria used to include trigger events for analysis were determined by analyzing video of a single game 30 days apart.

Label (Choices)	Inclusion Criteria	Intra-Rater Agreement			
		Percent Yes		Percent Agreement	Kappa (95% CI)
		Session 1	Session 2		
Potential Trigger (Yes, No)	Clear evidence of helmet contact and/or head motion	54%	47%	92%	0.82 (0.74, 0.91)
On Screen (Yes, No)	Player must be within the camera view	52%	48%	92%	0.86 (0.79, 0.93)
Unobstructed (Yes, No)	There must be a clear, unobstructed view	71%	77%	89%	0.72 (0.53, 0.90)

Table 2.

Inclusion criteria used to determine further head impact video analysis for determining a video observed head impact location. Included are interrater and intrarater agreements on applying the inclusion criteria to a 60-impact data subset and the interrater and intrarater agreement on categorizing video observed impact locations according to the HIT System definitions.

Label (Choices)	Inclusion Criteria	N	Interrater Agreement				Intrarater Agreement			
			Percent Yes Rater 1	Percent Yes Rater 2	Percent Agreement	Kappa (95% CI)	Percent Yes Session 1	Percent Yes Session 2	Percent Agreement	Kappa (95% CI)
On Field (Yes, No)	Player must be on the field	60	92%	97%	95%	0.55 (0.11, 0.99)	92%	92%	100%	1.00 (1.00, 1.00)
On Screen (Yes, No)	Player must be within the camera view	60	80%	82%	98%	0.94 (0.84, 1.00)	80%	80%	100%	1.00 (1.00, 1.00)
Unobstructed (Yes, No)	There must be a clear, unobstructed view	48[a]	83%	96%	85%	0.32 (−0.02, 0.66)	83%	81%	98%	0.93 (0.79, 1.00)
Impact Evidence (Yes, No)	Clear evidence of helmet contact and/or head motion	48[a]	83%	94%	85%	054 (0.08, 1.00)	83%	92%	88%	0.44 (0.07, 0.80)
HIT System Location (Yes, No)	A clear HIT System impact location is observed on the player's helmet	48[a]	75%	94%	77%	0.19 (−0.10, 0.36)	69%	75%	94%	0.85 (0.68, 1.00)
HIT System Location (Front, Top, Right, Left, Back)	N/A	30	67%[c]	60%[c]	73%	0.52 (0.24, 0.80)	62%[b,c]	59%[b,c]	90%[b]	0.82[b] (0.63, 1.00)

[a]–Denotes that up to 12 impacts occurred off the screen and out of camera view. Therefore, only 48 impacts were assessed according to the remaining inclusion criteria

[b]–Denotes that 29 impacts were common to both session 1 and session 2 after a 60 impact reliability data set was evaluated for inclusion for further video analysis

[c]–Denotes that the front was the most common impact location observed in the interrater and intrarater assessments. Percentage of impacts categorized with the front location are within the Percent Yes columns within the table.

Table 3.

True Positive (TP), False Positive (FP), False Negative (FN), and True Negative (TN) definitions used to categorize Head Impact Telemetry (HIT) System impact trigger events cross-referenced with video observed impacts for High School Football Special Teams Plays on one central North Carolina team, 2017.

		Video Review	
		Head Impact Observed (n = 239)	**No Head Impact Observed (n = 78)**
HIT System Impact Filtering Algorithm Classification	**Valid Head Impact Classified by HIT System Algorithm (n = 188)**	**Estimated True Positives (TP)** (Algorithm Correct) **n = 166**	**Estimated False Positives (FP)** (Algorithm Incorrect) **n = 22**
	Non-Head Impact Classified by HIT System Algorithm (n = 129)	**Estimated False Negatives (FN)** (Algorithm Incorrect) **n = 73**	**Estimated True Negatives (TN)** (Algorithm Correct) **n = 56**
		Estimated Sensitivity = 166 / 239 = 69% **Estimated Specificity = 56 / 78 = 72%**	