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High Energy Side and Rear American Football Head Impacts Cause Obvious Performance Decrement on Video

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Abstract

The objective of this study was to compare head impact data acquired with an impact monitoring mouthguard (IMM) to the video-observed behavior of athletes' post-collision relative to their pre-collision behaviors. A total of n=83 college and high school American football players wore the IMM and were video-recorded over 260 athlete-exposures. Ex-athletes and clinicians reviewed the video in a two-step process and categorized abnormal post-collision behaviors according to previously published Obvious Performance Decrement (OPD) definitions. Engineers qualitatively reviewed datasets to check head impact and non-head impact signal frequency and magnitude. The ex-athlete reviewers identified 2305 head impacts and 16 potential OPD impacts, 13 of which were separately categorized as Likely-OPD impacts by the clinical reviewers. All 13 Likely-OPD impacts were in the top 1% of impacts measured by the IMM (ranges 40–100g, 3.3–7.0 m/s and 35–118 J) and 12 of the 13 impacts (92%) were to the side or rear of the head. These findings require confirmation in a larger data set before proposing any type of OPD impact magnitude or direction threshold exists. However, OPD cases in this study compare favorably with previously published impact monitoring studies in high school and college American football players that looked for OPD signs, impact magnitude and direction. Our OPD findings also compare well with NFL reconstruction studies for ranges of concussion and sub-concussive impact magnitudes in side/rear collisions, as well as prior theory, analytical models and empirical research that suggest a directional sensitivity to brain injury exists for single high-energy impacts.

Keywords

Concussion; American football; Head impact sensor; Mouthguard; Video review; Obvious performance decrement

INTRODUCTION

Millions participate yearly in contact sports in the United States. Hundreds of thousands of these athletes sustain concussions (CDC, 2011; Langlois et al., 2006), yet due to subjective symptom disclosure, a lack of objective diagnostic criteria, poor athlete concussion knowledge or purposeful withholding of symptomology, approximately 50% of concussions go undiagnosed and unreported (McCrea et al., 2004; Kerr et al., 2018; Kerr et al., 2016; Kerr et al., 2014). There are increasing concerns about the potential negative consequences of acute concussion and accumulation of head impact doses on neurologic health (Rowson et al. 2019; Stemper et al., 2018; Danshevar et al., 2011; Plassman et al., 2000; Jordan BD, 2000; McKee et al., 2009; Omalu et al., 2005; Guskiewicz et al., 2005; Omalu et al., 2010; Guskiewicz et al., 2007; Arbogast et al., 2013; Cantu RC, 1998; Cantu & Gean, 2010; Thomas et al., 2011.) Accurate and precise (e.g. low uncertainty) head impact monitoring data from helmet-based and body-worn sensors provide a platform to inform our understanding of the relationship between single head impact doses, accumulation of head impact doses and resulting effects on neurologic function.

American football impact monitoring dates back to Col. John Paul Stapp in the 1970's, with later decades experimenting with a variety of instrumented bite-blocks, helmets, headbands, skin patches, mouthguards and the like (Foust 1978, Duma et al. 2005, Greenwald et al. 2008, Funk et al. 2011, Camarillo et al. 2013, Rowson et al. 2013, Patton 2016, O'Connor et al. 2016, Wu et al. 2018, Kuo et al. 2018). In the past decade, researchers have challenged sensor technologies to increase measurement trustworthiness so that new possibilities of analyzing specific head impact(s) and impact-specific decisions can be realized: "*accurate measures of individual exposure will yield a direct estimate of the human tolerance*" (Meaney et al. 2014), "*as more accurate sensors are designed…*" (Elliott et al. 2015), "*valid methods of measuring the direction and severity of on-field head impacts are needed*" (Siegmund et al. 2016) and sensors "*may not consistently record head impacts or forces transmitted to the brain*" (Harmon et al. 2019). In addition to low uncertainty kinematics estimates, qualitative video confirmation of head impacts has gained traction in the past few years as being very useful to pair with impact monitoring data (Bartsch et al. 2014, Hendricks et al. 2016, Makdissi & Davis 2016a, Makdissi & Davis 2016b, Press & Rowson 2017, Gardner et al. 2017, Kuo et al. 2018, Echemendia et al. 2018, Bruce et al. 2018, Gardner et al. 2018a, Lessley et al. 2018, Gardner et al. 2018b, Davis et al. 2019, Bartsch et al. 2019a, Bartsch 2019b, Kieffer et al. 2019, Bartsch et al. 2020a, Bartsch et al. 2020b (in press), Elbin et al. 2020, Patton et al. 2020, Zuckerman et al. 2020). An emerging benefit of such video reviews is that objective visible signs (VS) such as motor incoordination, lying motionless, impact seizure, among others can be documented (Bruce et al. BJSM 2017 NHL).

First done by the Australian Football League (AFL), clinicians have aimed to combine VS observations with head impact mechanisms to see if concussion diagnostic accuracy can be improved by more precisely identifying athletes who merit observation (Makdissi & Davis 2016a, b). In the past few years as a result of the new appreciation for VS video observations, professional leagues like the National Football League (NFL), National Rugby League (NRL) and National Hockey League (NHL) have followed suit by enacting measures to try and identify at-risk athletes using video review and live-game spotters (Elbin et al. 2020, Zuckerman et al. 2020). In American football specifically, an NFL study found that 74% of players with diagnosed concussions had at least one post-impact VS on video, though the concussion diagnostic sensitivity and specificity for VS from video alone were 73% and 65%, respectively(Elbin et al. 2020).

The objective of this study was to compare head impact data acquired with an impact monitoring mouthguard (IMM) to the video-observed behavior of athletes' post-collision relative to their pre-collision behaviors. Abnormal post-collision behaviors were noted according to Obvious Performance Decrement (OPD), which was based off definitions proposed by Davis et al. 2019. We sought to quantify the range and percentile rank of the impact kinematics measured by the IMM for the OPD impacts in comparison to the non-OPD impacts.

METHODS

Study Plan

The Study consisted of several components. First, athletes were consented and instrumented with an impact monitoring mouthguard. Then, during gameplay, instrumented athletes were video recorded. Afterwards the videos were scrutinized by two ex-Athlete Reviewers and potential collision, and head impact, timepoints identified. Athlete Reviewers also noted any timepoints where the players sustained potential OPD impact(s). After the Athlete Review was done, a panel of Clinician Reviewers examined and rated the potential OPD impacts. Engineers then reviewed kinematic traces from the IMM of the top 30 verified head impacts, inclusive of all OPD impacts, as well as all head impacts for any potential OPD player during the game, spot checks for another 1–2% of verified head impacts for non-OPD players and dozens of datasets from non-head impact events. Finally, the video-confirmed head impacts were paired by their timestamps to the engineer-reviewed kinematic data traces.

On-Field Data

The Institutional Review Board at the Medical College of Wisconsin approved all protocols. The IMM was a prototype Generation 1.3 wireless 3a3ω accelerometer and gyroscope-based data acquisition system (DAQ) hermetically sealed inside an athletics mouthguard. The DAQ included kinematic sensors with sufficient range and bandwidth to estimate skull motion during impact (ADXL372, Analog Devices, Boston MA; BMG250, Bosch, Gerlingen Germany), on-board firmware for data transform from teeth to head center of gravity (CG), nonvolatile flash memory for storage, wireless rechargeable battery and wireless data offload using Bluetooth low energy. While the IMM outputs six degree of freedom kinematic time traces, only scalar peak linear acceleration change (PLA), scalar peak angular acceleration change (PAA), scalar peak linear velocity change (PLV), scalar peak angular velocity change (PAV), kinetic energy transfer based on change in linear and angular velocities (KET) and impact location are reported according to an analytical head impact model from Bartsch et al. 2014. Linear peak kinematics are at the CG and the PLA has been found to be within 4%

of Reference ((Tyson et al. 2018), Liu et al. 2020 (submitted)). Additional details on the IMM data acquisition can be found in the APPENDIX.

A total of 83 athletes wore the IMM during video-recorded American football games from Fall 2019. The athlete distribution was 1% Division I college, 63% Division III college and 36% High School. There were 260 athlete-exposures (AE), with one AE being defined as an athlete wearing the IMM in a video-recorded game. Because the IMM system was being deployed for the first time at scale, the first few months of data collection presented challenges for the Study Team. For some early season games the amount of data collected exceeded the capacity of data transmission from the IMM through a local hub to the cloud.For some games acquiring video of the entire field of play was not possible. There were also athletes who aggressively chewed on the IMM and broke the internal hardware during a game. Due to these technical issues, the large number of athletes instrumented and the frequency of data collection, some early season data was incomplete. Later in the season the system ease-of-use, and concept of operations, improved greatly.

Ex-Athlete Video Reviewers

For the initial video review, this study utilized two reviewers who were former athletes, with at least 10 years of American football training, experienced in video breakdown of dozens of American football games, knowledge about movement norms of each playing position, expected normal player behavior for each type of play and a personal understanding of what typically happens on the field during normal and high-energy plays for high school and college American football.

The athlete reviewers were first provided continuous time-stamped video of at least 30 frames per second, at least 1024x768 resolution and at least 720i format with synchronous time as the IMM (using a free app Timestamp Camera, available on the Apple Store), and reviewed video together to ensure they found collisions sequences likely to have head impacts for every athlete during the entire game. A collision sequence is broadly defined as any play which could have head impact(s), where an athlete appears to collide one or more times with another player or the field, such as a lineman who collides with two different players within a few seconds. Players were also observed on the sideline to quantify any out-of-play impacts. A sideline view was taken of players during on-field action, and if necessary, additional video sources such as Hudl or team-uploads to YouTube were mined to confirm collisions or to view collisions from a different angle. The athlete reviewers first agreed whether it looked like a collision occurred during the play according to methods established by Kuo et al. (2018), and second whether after an athlete was involved in a collision, that there was clear visual evidence of an abnormal player reaction which we called Obvious Performance Decrement (OPD). Each athlete reviewer recorded their own opinion of the OPD cases, including situations where they disagreed with each other. These comments are provided in the APPENDIX. The immediate incapacitation and altered balance and/or movement coordination OPD reactions were based on the consensus visible sign definitions from Davis et al. 2019, and included additional football-specific atypical post-impact behaviors:

1. Immediate incapacitation

    - Potential loss of consciousness, lying motionless>2sec*
    - Fencing response
    - Tonic posturing*
    - Decorticate primitive reflex*
    - Falls to ground in unprotected manner*
    - Blank/vacant look*

2. Altered balance and/or movement coordination
    - Slow-to-get up*
    - Gross motor instability*
    - Functional disturbance - Staggering/stumbling/tripping/falling*
    - Movement - slow/labored/abnormal/unstable
3. Atypical post-impact behavior
    - Clutches head
    - Confusion/disorientation
    - Irregular sport-related actions – lines up in wrong position, incorrect playing style (runs away from contact), playing style gives opponent obvious advantage (blocks wrong team), unsure of location on field, unsure of where bench is
    - Player seeks out sideline caregivers
    - Teammate seeks out sideline caregivers on player’s behalf

*indicates consensus visible signs defined by Davis et al. 2019

For games where any player exhibited potential OPD behavior the reviewers re-reviewed all collisions for the athlete during the game to confirm OPD behavior. The video review summaries are provided in the APPENDIX. After the video reviews and OPD double-checks were done, the athlete reviewers were provided time stamped IMM data and the comparison between video review and IMM-measured impacts was initiated. Obvious IMM non-head impact and data without corresponding video were removed (e.g. before game, between plays, halftime, after game, between quarters, on sideline).

After the season was over, both athlete reviewers re-reviewed the top 1% of IMM-reported impact magnitudes (whether a potential OPD impact or not) and confirmed visual findings in a similar method to Stemper et al. (2018).

Clinician Video Review

Videos that included potential OPD player reactions were then reviewed by a panel of clinician experts – one NFL video spotter, one NFL sideline physician, two NFL unaffiliated neurological consultants and three athletic trainers with 10+ years of American football experience – to confirm whether the video reviewers' identification of potential OPD aligned with clinician findings. Clinicians developed majority consensus on whether impacts looked like No OPD, Questionable OPD and Likely OPD. The Likely OPD cases were ones that all clinicians were certain that the athlete's post-collision behavior on video fit into the OPD operational definitions. The Questionable OPD cases were ones where most clinicians thought it was plausible that video showed OPD behavior, but they could not tell for certain. The No OPD cases were ones where most clinicians felt the athlete's pre- and post-collision behavior had zero OPD behavior on video.

Engineer Time Trace Review

After video reviews were done, two engineers confirmed kinematic data quality for the top 1% of impacts based on Bartsch et al. (2014). To verify the thoroughness of the video reviews, spot checks were also done for another 1–2% of impact data sets selected at random across the distribution to ensure qualitative video findings agreed with IMM-reported head impact dose kinematics. Dozens of video-reported non-head impact events were also examined to confirm their lack of conformance to a head impact model (e.g. high noise, high frequency content, non-impact motion).

Data Analysis

Statistical analyses for the video-verified IMM data included summarizing percentage of impacts by location on the head, providing summary distributions by percentage of head impact severity for PLA, PAA, PLV, PAV and KET, and analyzing the top 1% and 5% of impacts for potential OPD cases.

RESULTS

Out of a total of 63,238 IMM data sets collected (roughly 240 per A-E), after combining video reviewer a total of n=2305 head impacts were confirmed. There were 1716 head impacts (74%) with PLA>10g and 589 head impacts (26%) with PLA<10g. There were no cases of a video-reported collision sequence where there was no IMM data (e.g. false negative head impact measurement). About 60,000 non-head impact data sets were removed because of the video review.

The summary distribution of head impacts by estimated CG PLA >10g (n=1716) is displayed in Figure 1a. Like the PLA distribution, the PAA, PLV, PAV and KET had distributions skewed toward lower magnitudes and are shown in Figure 1b–e. By impact location, Figure 1f, 67% were to the front, 20% were to the sides and 13% were to the back of the head. The top 1% of rounded head impact peaks were PLA >50g, PLV >4m/s, PAA >4,000rad/s^2, PAV >20rad/s and KET>40J.

All OPD impacts identified by the ex-Athlete reviewers occurred in the top 2% of impacts by PLV. For these impacts, Reviewer #1 identified 14 impacts as OPD, while Reviewer #2 identified 15 impacts as OPD. Thirteen of these OPD impacts were common to both reviewers. After final review by the clinical experts, 13 impacts were classified as Likely OPD, 2 impacts as Questionable OPD and 16 impacts as No OPD. See Table 1 for video review summary, and Table A1 for complete video review details of the top 30 impacts by

PLV. All potential OPD impacts flagged by non-clinician reviewers were within the top 5% by impact magnitudes.

For side and rear impacts, twelve of the top fifteen (12/15, 80%) events (PLA range 40–100g, PAA range 1,700–5,000rad/s^2, PLV range 3.3–7.0m/s, PAV range 15–30rad/s, KET range 34–118J) resulted in clinician-classified Likely OPD, see Table 2 and Figures 2a–b. There were two Likely OPD cases – one to the side and one to the rear – where the athletes appeared to lose consciousness and were lying motionless on the field. For frontal impacts, one of the top fifteen (1/15, 7%) events (PLA 62g, PAA 2,529rad/s^2, PLV 4.0m/s, PAV 9rad/s, KET 38J), resulted in Likely OPD.

DISCUSSION

The goal of this study was to characterize head impact kinematics associated with OPD in college and high school football players using video-verified head impact data collected using an impact monitoring mouthguard

There were 15 impacts – less than 1% of the 2305 video verified impacts – flagged by non-clinician video reviewers as potential OPD. Clinician reviewers decided that 13 of these impacts were ‘Likely OPD’ and 2 were ‘Questionable OPD’. The OPD impacts in this study compared favorably to previously published data on OPD (*aka “No-Go”*) events (Bartsch et al. 2019a, Bartsch et al. 2019b, Bartsch et al. 2020a, Bartsch et al. 2020b). That previous work found that 100% (8/8) of the OPD cases in American football occurred to the side and rear of the head, and that these impacts were all in the top 1% by PLA, PLV and KET impact magnitude, approximately 50–90g, 3–7m/s and 40–120J, respectively.

The consistency between the OPD impact magnitudes and locations in the current study and in prior studies could inform future concussion surveillance. In particular, the NFL has for several years used clinical video reviewers and clinical gameplay observers to identify single head impacts in real-time when athletes appear affected and reported that 74% of concussed players had a visible sign (Zuckerman et al. 2020). Being able to also provide observers with reliable head impact kinematics data and a sense of how an impact’s magnitude and location relates to OPD events could be helpful. Reliable data could also ensure that all athletes who sustain a large head impact – whether initially unnoticed by observers, seen to be OPD on video, diagnosed concussive, or with no ultimate clinical findings – be more readily identified and potentially evaluated. Reliance on video surveillance or head impact monitoring systems alone, however, should not be considered a sufficient replacement for clinical observation and evaluation.

When comparing OPD impacts observed in this study to the NFL concussion biomechanics reconstruction studies (Newman et al. 2000a, Newman et al. 2000b, Pellman et al. 2003 Neurosurgery), the results are quite interesting. First, those authors pointed out that seminal early work by Stapp et al. (1961) and Patrick et al. (1965) estimated the human tolerance to padded head impacts in the range of PLA 40–80g. While not definitive, most of our OPD impact magnitudes fall within this PLA range. Second, the NFL reconstruction authors’ estimated ranges of concussion-causing PLA, PLV and KET to the side/rear were 50–140g, 4–10m/s and 40–250J, and non-concussion impacts to side/rear to be 20–80g, 3–6m/s and 20–80J, respectively. The OPD impacts we collected in this study were mostly at the median or lower of the NFL concussion-causing ranges, and at the median or higher of the NFL non-concussion ranges. This makes sense: in American football collisions the NFL data likely supply an upper bound on *human tolerance* to side/rear high energy impacts.

The NFL laboratory reconstruction authors also thought that concussion/mild TBI in their impacts occurred mainly from high energy lateral, oblique and rear head impacts and that the head might be more sensitive to lateral than to frontal impacts. Several other authors have published similar thoughts and experimental data to support brain directional sensitivity ideas over many decades (Holbourn et al. 1943, Gennarelli et al. 1987, McIntosh et al. 2000, Zhang et al. 2001, Kleiven 2003, Kleiven 2005, McIntosh et al. 2014, Elkin et al. 2019). Based on our current study, and the published IMM data and video review OPD findings, we may be observing in the ‘living laboratory’ that the brain does, in fact, have a directional sensitivity to the highest energy side and rear impacts. Between this study and the previously published IMM data (Bartsch et al. 2019a, Bartsch et al. 2019b, Bartsch et al. 2020a, Bartsch et al. 2020b), 95% of OPD impacts were to the side/rear despite only 35% of all video-verified impacts occurring to the side/rear of the head.

Explanations for observed OPD directional sensitivity may be related to kinetic and structural mechanisms. One explanation may be mass/inertia dependent; when a subject is aware of an oncoming impact like in a frontal blow, they may brace and thereby engage a larger effective mass to attenuate the impact. This would result in a lower acceleration and velocity change, and lower energy transfer to the brain. When a subject sustains a side or rear impact, they may not be able to brace in the same manner and there could be a larger acceleration/velocity change, and energy transfer to the brain. Video-verified collisions showed several athletes who sustained impacts where bracing would have been very difficult, when an unprotected head-to-ground impact occurred. Another potential mechanism may be dependent on the anatomic location for different brain function. Side and rear impacts may have a greater effect on areas of the brain which regulate vestibular-ocular, vestibular-spinal, and ocular-motor functions. Impairment of these functions would be more likely to result in OPDs observable during video review. Alternatively, frontal impacts may have a greater effect on areas of the brain which regulate functions such as emotion, language, and personality which would be less likely to result in OPDs and therefore not observed during video review.

We acknowledge the limited understanding of the mechanistic basis for OPD, impact magnitude and impact direction. Pairing OPD video observations with low-uncertainty impact monitoring data is not a clinical panacea at this point. We believe tying together impact dosing with OPD observations is an important step toward accurately quantifying head impact dose-response relationships. In the future, it is hoped that use of good quality impact monitoring data may lead to more targeted clinical efforts to oversee athlete impact doses.

Regarding the rest of the data, the two Reviewers video-verified head impacts in games in n=83 American football players over 260 AE. A total of 2305 impacts were video verified, with 1716 having PLA greater than 10g. For PLA<10g the Reviewers video-confirmed 589 inertial and/or head contacts that appeared ‘small’ on video. Based on these results, we think there were likely many hundreds – or thousands – of additional minor inertial/head contacts collected by the IMM with PLA <10g but were not notable to record as such by the Reviewers. Because of the immense work that would have been required to re-review the videos to extract all of the PLA<10g events, and the fact that head motions in this range are on par with activities of daily living, we decided it was not necessary to re-review videos for PLA<10g. In the future if head impact doses with PLA<10g demonstrate engineering or clinical importance, we may go back and re-review the videos to extract all these types of minor head motion events.

The PLA>10g distributions shown in Figure 1, with the top 1% of impacts occurring above approximately 50g, were like American football distributions published previously using a similar data collection and video reviewer methodology (Bartsch et al. 2019a, Bartsch et al. 2020a). While individual athlete and positional impact distribution variances no doubt existed and were obscured by reporting of individual impacts as part of a population distribution, the results shown in Figure 1 confirmed that the impact dosing was consistent between the current study and prior research. Also, the range of impact magnitudes, as well as impact locations confirmed that on-field data in this study fell within the ranges of calibration from the laboratory with the exception that the Virginia Tech Sensor 5 laboratory tests in the APPENDIX did not calibrate the IMM response to facemask impacts. However, facemask impact calibrations have been published elsewhere (Bartsch et al. 2014, Hedin et al. 2016, Bartsch et al. 2019a, Bartsch et al. 2020a, Domel et al. 2020-submitted) and the impacts collected in this study fell within the published facemask calibration ranges.

Because of a lack of trusted reference in the ‘living laboratory’, video and impact monitoring results carry a degree of doubt. Video review has a qualitative and subjective nature since players can block the view, images can be blurry and the main velocity change of the head occurs in about 15 ms, while the typical video camera captures a frame every 15 to 30 ms. Head impact monitoring data is subject to difficulties of confirming high signal-noise ratio in the ‘living laboratory’. Ensuring sufficient coupling to the skull is necessary, as well as engineering quality checks of data to confirm reported impact doses are physically realistic. Although video observations and impact dose estimates have some degree of doubt when each is viewed *in isolation* and without consideration of the other, their utility increases when both data sources are combined. If one can reliably determine when an impact monitor is, and is not, firmly coupled to the teeth then it becomes easier to tie impact dose data to video observations. Likewise, if one is able to check impact severities relative to what the sensor reports – e.g. a “small” sensor impact ought to look small and a “large” sensor impact should look large – on video prior to examining kinematic data traces, then some level of trust can be developed for both the video and monitoring methods, even when one of them has lower signal-noise ratio. Finally, a good check on the method is to do a laboratory reconstruction of impacts. If data and video agree, then the reconstruction should be straightforward. If not, then the reconstruction could be extremely difficult or impossible, and a re-analysis of both data and video quality are merited.

One study limitation is that the KET estimate does not reflect the true change in kinetic energy due to the impact. While the PLV and PAV reflect the absolute velocity changes, the total kinetic energy change is unknown because we do not know the initial linear or angular velocity of the athlete’s head. However, the KET – and potentially the rate of energy change – provides a simple way to quantify the combined effects of linear and rotational changes in a single metric, can be easily replicated in lab testing, and have been used by other authors to indicate the overall impact dosing (Newman et al. 2000a, Pellman et al. 2003). And the KET estimate can also provide a simple to grasp cumulative impact dose quantifier, since summing energy or power has an easier to grasp physical basis than summing peaks of acceleration or complex risk function outputs. This is one area where computational simulation may help us understand the effects of an inaccurate KET estimate on potential injury risk. Pre-impact velocity conditions can be modified virtually to quantify differences in brain stress and strain.

Another limitation of this study is that observing an OPD impact on video does not constitute a clinical diagnosis or take the place of a clinical exam for an athlete observed with concussion signs and symptoms. Additionally, on-field OPDs may be associated with very acute disturbances and/or low-level deficits that do not exceed the thresholds for clinically diagnosable concussion, or other non-concussion-related injuries. Therefore, the validity of an OPD observation with respect to a clinical concussion diagnosis remains unknown. Concussion reporting subjectivity is a well-known issue (Baugh et al., 2019). So it is possible that historical concussion tolerance and/or concussion risk curves, most of which have not been able to tie a specific impact on video to a clinically observed sign or symptom, are based on semi-random subject reporting. This poor connection between the injury and the impact that caused the injury could reveal the real benefit of our OPD analysis – we have attempted to remove subjective self-reporting and instead provide a more objective method for identifying impacts that could result in higher risk of an injury. For these reasons, in future work we aim to notify study staff soon after a high-energy head impact is recorded and start to link the impact kinematics to quantifiable clinical findings and diagnoses for injured and uninjured athletes alike.

In conclusion, we found that the highest energy side and rear impacts to the head were associated with abnormal post-collision behaviors in 83 college and high school American football players. Athlete and clinical reviewers categorized abnormal post-collision behaviors according to Obvious Performance Decrement (OPD) definitions, finding evidence of Likely OPD in 13 of 2305 video-verified head impacts measured with an impact monitoring mouthguard system. These 13 Likely-OPD impacts were all in the top 1% of impacts when ranked by magnitude, and fell in the ranges of 40–100g, 3.3–7.0m/s and 35–118J. These findings require confirmation in a larger data set before proposing any injury thresholds for OPD impacts.

Supplementary Material

Refer to Web version on PubMed Central for supplementary material.

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REFERENCES

1. Centers for Disease Control. Nonfatal sports and recreation related traumatic brain injuries among children and adolescents treated in emergency departments in the United States, 2001–2009. United States Centers for Disease Control and Prevention-Morbidity and Mortality Weekly Report (MMWR); 2011 Report No.: MMWR 60(39).
2. Langlois JA, Rutland-Brown W, Wald MM. The epidemiology and impact of traumatic brain injury: a brief overview. J Head Trauma Rehabil. 2006; 21:375–8. [PubMed: 16983222]
3. McCrea M, Hammeke T, Olsen G, Leo P, Guskiewicz K. Unreported concussion in high school football players: implications for prevention. Clin J Sport Med. 2004; 14:13–7. [PubMed: 14712161]
4. Kerr ZY, Register-Mihalik JK, Kay MC, DeFreese JD, Marshall SW, Guskiewicz KM. Concussion nondisclosure during professional career among a cohort of former National Football League athletes. Am J Sports Med. 2018;46(1): 22–29. [PubMed: 28942673]
5. Kerr ZY, Register-Mihalik JK, Kroshus E, Baugh CM, Marshall SW. Motivations associated with nondisclosure of self-reported concussions in former collegiate athletes. Am J Sports Med. 2016;44(1):220–225. [PubMed: 26582799]
6. Kerr ZY, Register-Mihalik JK, Marshall SW, Evenson KR, Mihalik JP, Guskiewicz KM. Disclosure and non-disclosure of concussion and concussion symptoms in athletes: review and application of the socio-ecological framework. Brain Inj. 2014;28(8):1009–1021. [PubMed: 24738743]
7. Rowson B, Stitzel JD & Duma SM Special Issue on the NCAA-DoD CARE Consortium Research. Ann Biomed Eng 47, 2045–2047 (2019). [PubMed: 31591661]
8. Stemper BD, Shah AS, Harezlak J et al. Comparison of Head Impact Exposure Between Concussed Football Athletes and Matched Controls: Evidence for a Possible Second Mechanism of Sport-Related Concussion. Ann Biomed Eng 47, 2057–2072 (2019). [PubMed: 30362082]
9. Daneshvar DH, Riley DO, Nowinski CJ, McKee AC, Stern RA, Cantu RC. Long-term consequences: effects on normal development profile after concussion. Phys Med Rehabil Clin N Am. 2011; 22:683,700, ix. [PubMed: 22050943]
10. Plassman BL, Havlik RJ, Steffens DC, Helms MJ, Newman TN, Drosdick D, et al. Documented head injury in early adulthood and risk of Alzheimer’s disease and other dementias. Neurology. 2000; 55:1158–66. [PubMed: 11071494]
11. Jordan BD. Chronic traumatic brain injury associated with boxing. Semin Neurol. 2000; 20:179–85. [PubMed: 10946737]
12. McKee AC, Cantu RC, Nowinski CJ, Hedley-Whyte ET, Gavett BE, Budson AE, et al. Chronic traumatic encephalopathy in athletes: progressive tauopathy after repetitive head injury. J Neuropathol Exp Neurol. 2009; 68:709–35. [PubMed: 19535999]
13. Omalu BI, DeKosky ST, Minster RL, Kamboh MI, Hamilton RL, Wecht CH. Chronic traumatic encephalopathy in a National Football League player. Neurosurgery. 2005; 57:128–34.
14. Guskiewicz KM, Marshall SW, Bailes J, McCrea M, Cantu RC, Randolph C, et al. Association between recurrent concussion and late-life cognitive impairment in retired professional football players. Neurosurgery. 2005; 57:719–26. [PubMed: 16239884]

15. Omalu BI, Fitzsimmons RP, Hammers J, Bailes J. Chronic traumatic encephalopathy in a professional American wrestler. J Forensic Nurs. 2010; 6:130–6. [PubMed: 21175533]
16. Guskiewicz KM, Mihalik JP, Shankar V, Marshall SW, Crowell DH, Oliaro SM, et al. Measurement of head impacts in collegiate football players: relationship between head impact biomechanics and acute clinical outcome after concussion. Neurosurgery. 2007; 61:1244–52. [PubMed: 18162904]
17. Arbogast KB, McGinley AD, Master CL, Grady MF, Robinson RL, Zonfrillo MR. Cognitive Rest and School-Based Recommendations Following Pediatric Concussion: The Need for Primary Care Support Tools. Clin Pediatr (Phila). 2013;52(5):397–402. [PubMed: 23447397]
18. Cantu RC. Second-impact syndrome. Clin Sports Med. 1998; 17:37–44. [PubMed: 9475969]
19. Cantu RC, Gean AD. Second-impact syndrome and a small subdural hematoma: an uncommon catastrophic result of repetitive head injury with a characteristic imaging appearance. J Neurotrauma. 2010; 27:1557–64. [PubMed: 20536318]
20. Thomas M, Haas TS, Doerer JJ, Hodges JS, Aicher BO, Garberich RF, et al. Epidemiology of sudden death in young, competitive athletes due to blunt trauma. Pediatrics. 2011;128: e1–8. [PubMed: 21690117]
21. Foust DR. Minutes from the Sixth Annual International Workshop on Human Subjects for Biomechanical Research 23 October 1978; i–xv, Ann Arbor, Michigan.
22. Duma SM, Manoogian SJ, Bussone WR, Brolinson PG, Goforth MW, Donnenwerth JJ, Greenwald RM, Chu JJ, Crisco JJ. Analysis of Real-time Head Accelerations in Collegiate Football Players. Clin J Sport Med 2005; 15:3–8. [PubMed: 15654184]
23. Greenwald RM, Gwin JT, Chu JJ, Crisco JJ: Head impact severity measures for evaluating mild traumatic brain injury risk exposure. Neurosurgery 2008; 62: 789–798. [PubMed: 18496184]
24. Funk JR, Cormier JM, Bain CE, Guzman H, Bonugli E, Manoogian SJ. Head and Neck Loading in Everyday and Vigorous Activities. Annals of Biomedical Engineering, Vol. 39, No. 2, 2 2011 pp. 766–776. [PubMed: 20960061]
25. Camarillo DB, Shull PB, Mattson J, Shultz R, Garza D An Instrumented Mouthguard for Measuring Linear and Angular Head Impact Kinematics in American Football. Annals of Biomedical Engineering, Vol. 41, No. 9, 9 2013, pp. 1939–1949. [PubMed: 23604848]
26. Rowson S and Duma SM. Brain Injury Prediction: Assessing the Combined Probability of Concussion Using Linear and Rotational Head Acceleration. Annals of Biomedical Engineering, Vol. 41, No. 5, 5 2013, pp. 873–882. [PubMed: 23299827]
27. Wu LC, Kuo C, Loza J, Kurt M, Laksari K, Yanez LZ, Senif D, Anderson SC, Miller LE, Urban JE, Stitzel JD, Camarillo DB. Detection of American Football Head Impacts Using Biomechanical Features and Support Vector Machine Classification. Scientific Reports, 2018, 8:855.
28. Kuo C, Wu L, Loza J, Senif D, Anderson SC, Camarillo DB. Comparison of video-based and sensor-based head impact exposure. PLoS ONE 13(6): e0199238, 2018. [PubMed: 29920559]
29. Patton DA. A Review of Instrumented Equipment to Investigate Head Impacts in Sport. Applied Bionics and Biomechanics. Volume 2016, Article ID 7049743.
30. O'Connor KL, Rowson S, Duma SM, Broglio SP. Head-Impact-Measurement Devices: A Systematic Review. Journal of Athletic Training, 2017;52(3):206–227. [PubMed: 28387553]
31. Meaney DF, Morrison B, Bass CD. The mechanics of traumatic brain injury: A review of what we know and what we need to know for reducing its societal burden. J Biomech Eng. 2014;136.
32. Elliott MR, Margulies SS, Maltese MR, Arbogast KB. Accounting for sampling variability, injury under-reporting, and sensor error in concussion injury risk curves. J Biomech. 2015; 48:3059–65. [PubMed: 26296855]
33. Siegmund GP, Guskiewicz KM, Marshall SW, DeMarco AL, Bonin SJ. Laboratory Validation of Two Wearable Sensor Systems for Measuring Head Impact Severity in Football Players. Ann Biomed Eng. 2016; 44:1257–74. [PubMed: 26268586]
34. Harmon KG, Clugston JR, Dec K, et al. American Medical Society for Sports Medicine position statement on concussion in sport. British Journal of Sports Medicine 2019; 53:213–225. [PubMed: 30705232]

35. Bartsch AJ, Samorezov S, Benzel EC, Miele VJ, Brett D. Validation of an “Intelligent Mouthguard” Single Event Head Impact Dosimeter. Stapp Car Crash Journal. 2014; 58:1–27. [PubMed: 26192948]
36. Hendricks S, O’Connor S, Lambert M, Brown JC, Burger N, Mc Fie S, Readhead C, Viljoen W. Video analysis of concussion injury mechanism in under-18 rugby. BMJ Open Sport Exerc Med 2016; 2: e000053 Doi:10.1136/bmjsem-2015-000053.
37. Makdissi M, Davis G. The reliability and validity of video analysis for the assessment of the clinical signs of concussion in Australian football. J SciMed Sport. 2016;19(10):859–863.
38. Makdissi M, Davis G. Using video analysis for concussion surveillance in Australian football. J SciMed Sport. 2016;19(12):958–963.
39. Press JN, Rowson S. Quantifying head impact exposure in collegiate women’s soccer. Clin J Sport Med. 2017;27(2):104–110. [PubMed: 26978008]
40. Gardner AJ, Howell DR, Levi CR, Iverson GL. Evidence of concussion signs in national rugby league match play: a video review and validation study. SportsMed—Open. 2017;3(1):29.
41. Echemendia RJ, Bruce JM, Meeuwisse W, Hutchison MG, Comper P, Aubry M. Can visible signs predict concussion diagnosis in the National Hockey League? Br J Sports Med. 2018;52(17):1149–1154. [PubMed: 28377445]
42. Bruce JM, Echemendia RJ, Meeuwisse W, Hutchison MG, Aubry M, Comper P. Development of a risk prediction model among professional hockey players with visible signs of concussion. Br J Sports Med. 2018;52(17):1143–1148. [PubMed: 28377444]
43. Gardner AJ, Howell DR, Iverson GL. A video review of multiple concussion signs in National Rugby League match play. Sports Med - Open. 2018;4(1):5. [PubMed: 29330738]
44. Gardner AJ, Kohler R, McDonald W, Fuller GW, Tucker R, Makdissi M. The use of sideline video review to facilitate management decisions following head trauma in super rugby. Sports Med - Open. 2018;4(1):20. [PubMed: 29797099]
45. Lessley DJ, Kent RW, Funk JR, et al. Video analysis of reported concussion events in the National Football League during the 2015–2016 and 2016–2017 seasons. Am J Sports Med. 2018;46(14):3502–3510. [PubMed: 30398897]
46. Bartsch AJ, McCrea MM, Hedin DS, Gibson PL, Miele VJ, Benzel EC, Alberts JL, Samorezov S, Shah A, Stemper BS. Laboratory and On-field Data Collected by a Head Impact Monitoring Mouthguard. Conf Proc IEEE Eng Med Biol Soc. 2019 7;2068–2072.
47. Bartsch A, Miele V, Alberts J, Benzel E, Shah A, Humm J, Stemper B, McCrea M. Estimates of High-Risk Single and Cumulative Head Impact Doses in American Football. Biomed Sci Instrum. Vol. 55(2): pp.224–229; 4 2019.
48. Davis GA, Makdissi M, Bloomfield P, et al. International study of video review of concussion in professional sports. Br J Sports Med. 2019;53(20):1299–1304. [PubMed: 30262454]
49. Kieffer EE, Pierce G, Vaillancourt C, Rowson S. In-Season Concussion Symptom Presentation in Men’s and Women’s Rugby. Biomed Sci Instrum. Vol 55(2): pp. 236–241; 4 2019.
50. Bartsch A, Dama R, Alberts J, Samorezov S, Benzel E, Miele V, Shah A, Humm J, McCrea M, Stemper B. Measuring Blunt Force Head Impacts in Athletes. Military Medicine, 185, S1:190:2020.
51. Bartsch A, Benzel E, Samorezov S, Miele V. Summary of accurate and precise head impacts collected on-ice in hockey players. ASTM International STP Proceedings from the 2019 International Ice Hockey Summit, Denver, Colorado, pp. 1–29, 2020 (in press).
52. Elbin RJ, Zuckerman SL, Sills AK, Crandall JR, Lessley DJ, Solomon GS. Sensitivity and Specificity of On-Field Visible Signs of Concussion in the National Football League. Neurosurgery, 0:1–8,2020.
53. Patton DA, Huber CM, McDonald CC, Margulies SS, Master CL, Arbogast KB. Video Confirmation of Head Impact Sensor Data from High School Soccer Players. American Journal of Sports Medicine, 2020;48(5):1246–1253. [PubMed: 32130020]
54. Zuckerman SL, Elbin RJ, Sills AK, Crandall JR, Lessley DJ, Moran CM, Moran CD, Solomon GS. Concussions in the National Football League: the evolution of video review for assessing the frequency and reliability of visible signs. Phys Sportsmed. 2020; 1–6.

55. Tyson AM, Duma SM, Rowson S. Laboratory Evaluation of Low-Cost Wearable Sensors for Measuring Head Impacts in Sports. J Appl Biomech. 2018 8 1;34(4):320–326. [PubMed: 29613824]
56. Newman JA, Shewchenko N, Welbourne E. A Proposed New Biomechanical Head Injury Assessment Function – The Maximum Power Index. Stapp Car Crash Journal, Vol. 44 (P-362), 2000-01-SC16.
57. Newman J, Barr C, Beusenberg M, Fournier E, Shewchenko N, Welbourne E, Withnall C. A New Biomechanical Assessment of Mild Traumatic Brain Injury Part 2 – Results and Conclusions. International Research Council on Biomechanics of Injury (IRCOBI), 2000.
58. Pellman EJ, Viano DC, Tucker AM, Casson IR, Waeckerle JF. Concussion in Professional Football: Reconstruction of Game Impacts and Injuries. Neurosurgery 53:799–814, 2003. [PubMed: 14519212]
59. Stapp JP: Human tolerance to severe, abrupt deceleration, in Gauer OH, Zuidema GD (eds): Gravitational Stress in Aerospace Medicine. Boston, Little, Brown and Co., 1961, pp 165–188.
60. Patrick LM, Lissner HR, Gurdjian ES: Survival by design: Head protection, in Proceedings of the 7th Stapp Car Crash Conference Warrendale, Society of Automotive Engineers, 1965, 483–499.
61. Holbourn AS. Mechanics of Head Injuries. The Lancet, 09 10 1943, p.438.
62. Gennarelli T, Thibault L, Tomei G, Wiser R, et al., “Directional Dependence of Axonal Brain Injury due to Centroidal and Non-Centroidal Acceleration,” SAE Technical Paper 872197, Proceedings of the 31st Stapp Car Crash Conference, 1987.
63. McIntosh AS, McCrory P, Comerford J. The dynamics of concussive head impacts in rugby and Australian rules football. Med Sci Sports Exerc, Vol. 32, No. 12, 2000, pp. 1980–1984. [PubMed: 11128839]
64. Zhang L, Yang KH, King AI. Comparison of Brain Responses Between Frontal and Lateral Impacts by Finite Element Modeling. Journal of Neurotrauma, Volume 18, Number 1, 2001, pp. 21–30. [PubMed: 11200247]
65. Kleiven S Influence of Impact Direction on the Human Head in Prediction of Subdural Hematoma. Journal of Neurotrauma, Volume 20, Number 4, 2003, pp. 365–379. [PubMed: 12866816]
66. Kleiven S. Influence of Direction and Duration of Impacts to the Human Head Evaluated Using the Finite Element Method. International Research Council on the Biomechanics of Impact (IRCOBI), 2005, pp. 41–57.
67. McIntosh AS, Patton DA, Fréchède B, et al. The biomechanics of concussion in unhelmeted football players in Australia: a case–control study. BMJ Open 2014;4: e005078.
68. Elkin BS, Gabler LF, Panzer MB, Siegmund GP. Brain tissue strains vary with head impact location: A possible explanation for increased concussion risk in struck versus striking football players. Clinical Biomechanics 64 (2019) 49–57. [PubMed: 29625747]
69. Hedin DS, Gibson PL, Bartsch AJ, Samorezov S. Development of a Head Impact Monitoring “Intelligent Mouthguard”. Conf Proc IEEE Eng Med Biol Soc 2016 Aug;2007–2009.
70. Domel A, Validation and Comparison of Instrumented Mouthguards in Measuring Head Kinematics and Brain Deformation in Football Impacts. ABME 2020 (submitted).
71. Baugh CM, Meehan WP 3rd, Kroshus E, McGuire TG, Hatfield LA. College Football Players Less Likely to Report Concussions and Other Injuries with Increased Injury Accumulation. J Neurotrauma. 2019;36(13):2065–2072. [PubMed: 30688141]

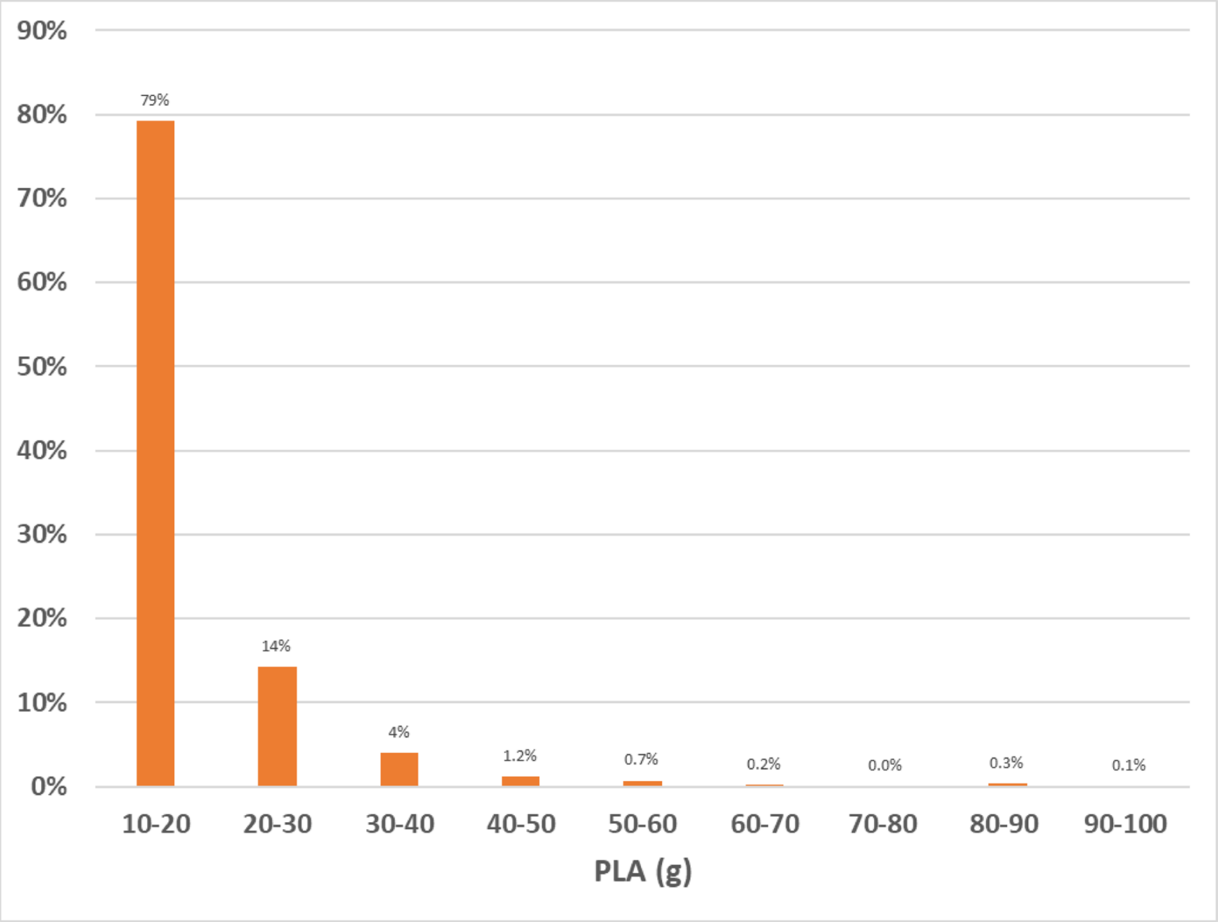

Fig. 1a.

Distribution of n=1716 video-verified head impacts with Peak CG Linear Acceleration (PLA) >10g from current study.

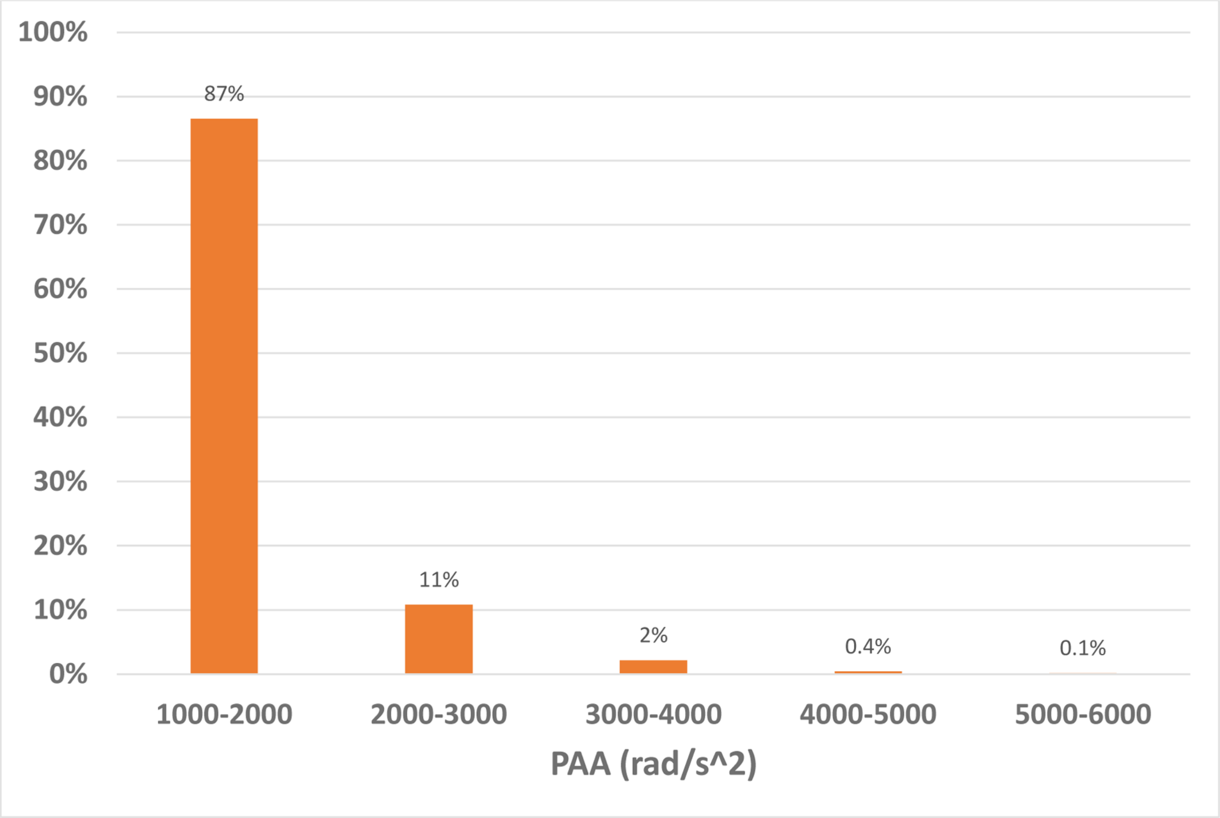

Fig. 1b.

Peak Angular Acceleration (PAA) head impact distribution.

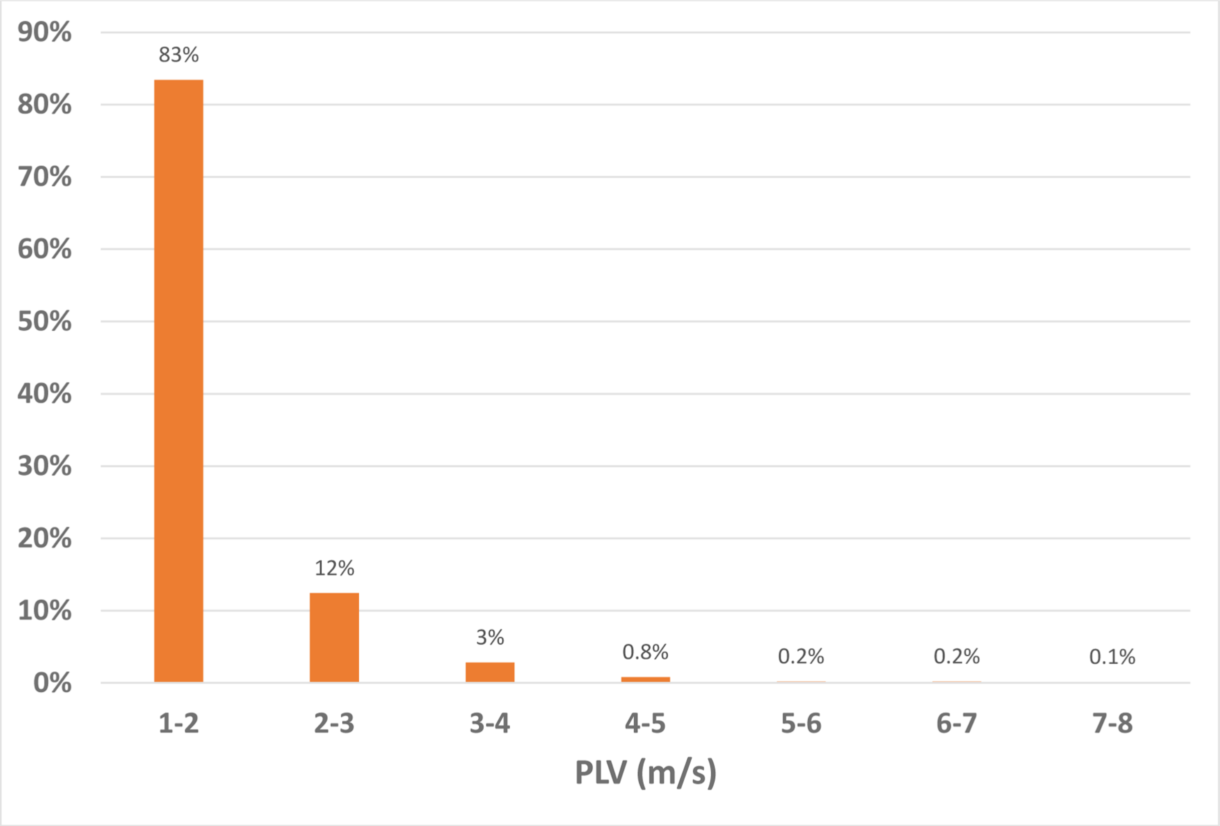

Fig. 1c.

Peak Linear Velocity (PLV) head impact distribution.

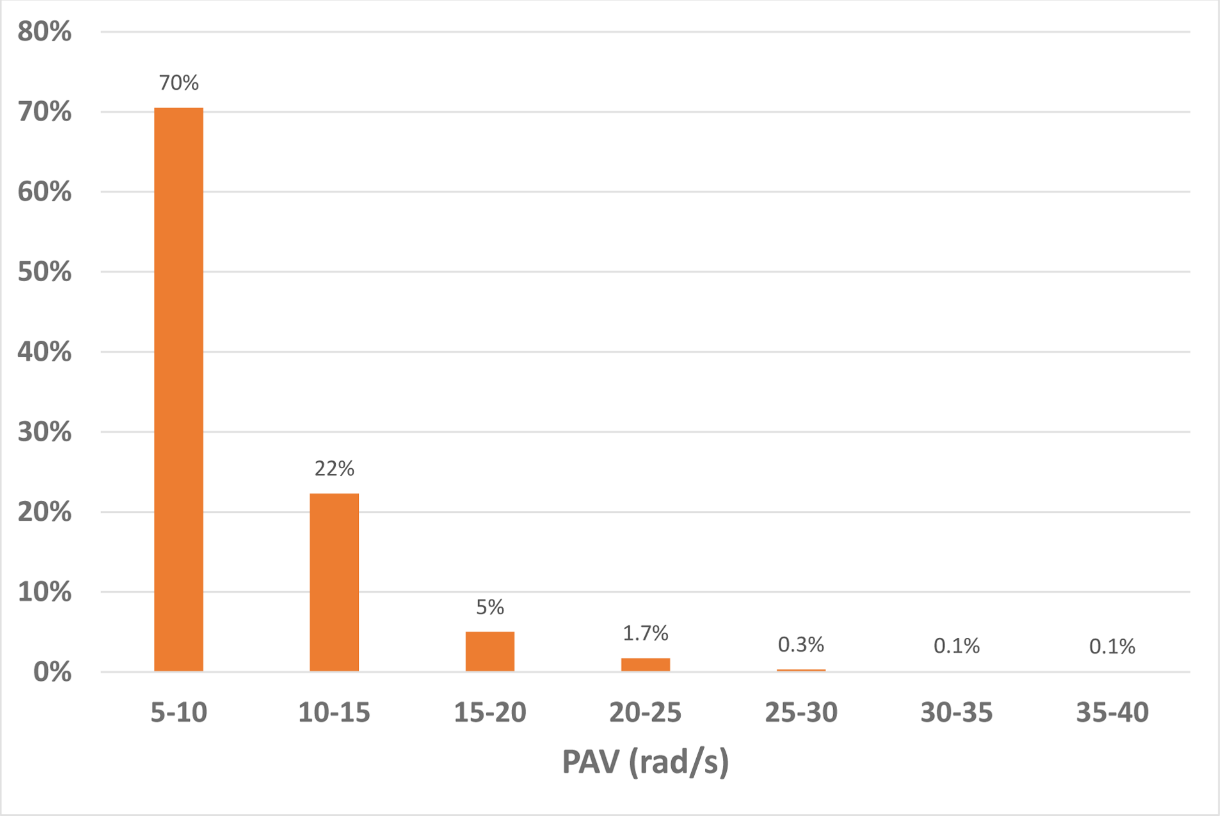

Fig. 1d.
Peak Angular Velocity (PAV) head impact distribution.

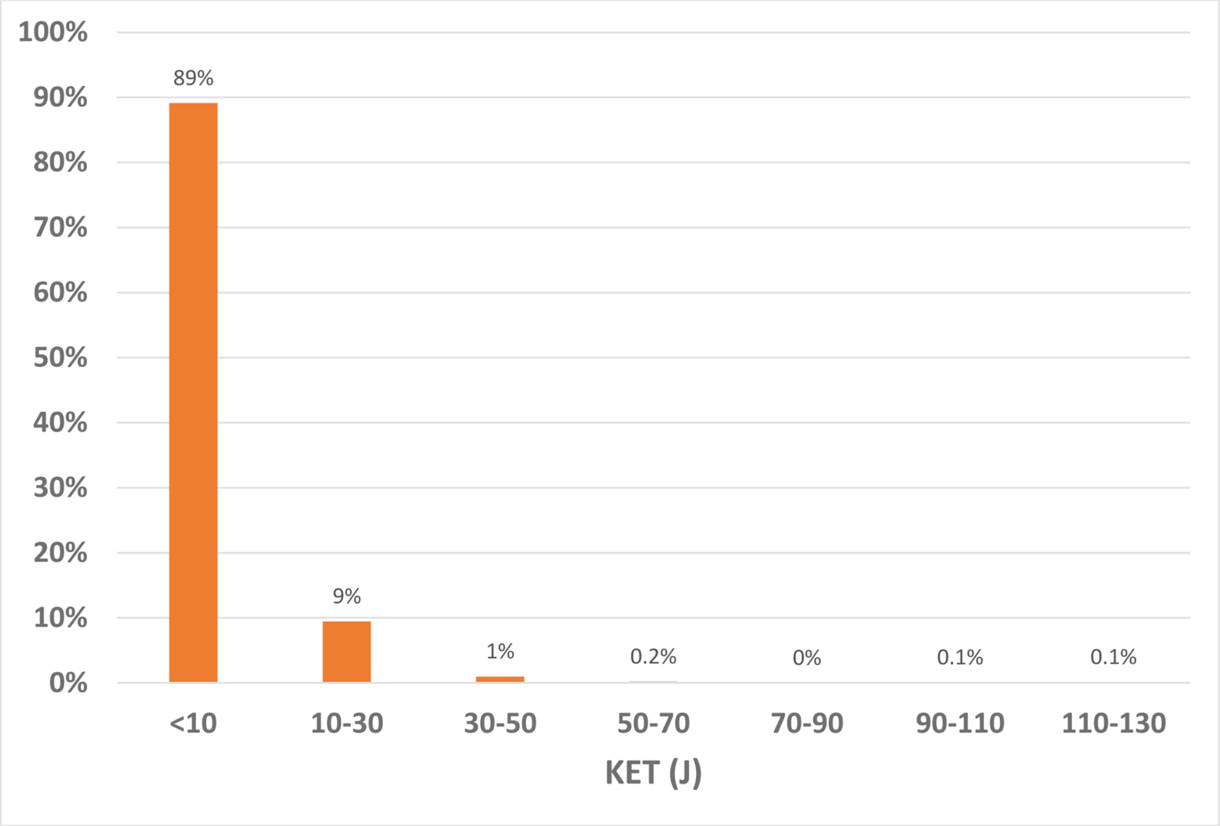

Fig. 1e.

Estimated Kinetic Energy Transfer (KET) head impact distribution.

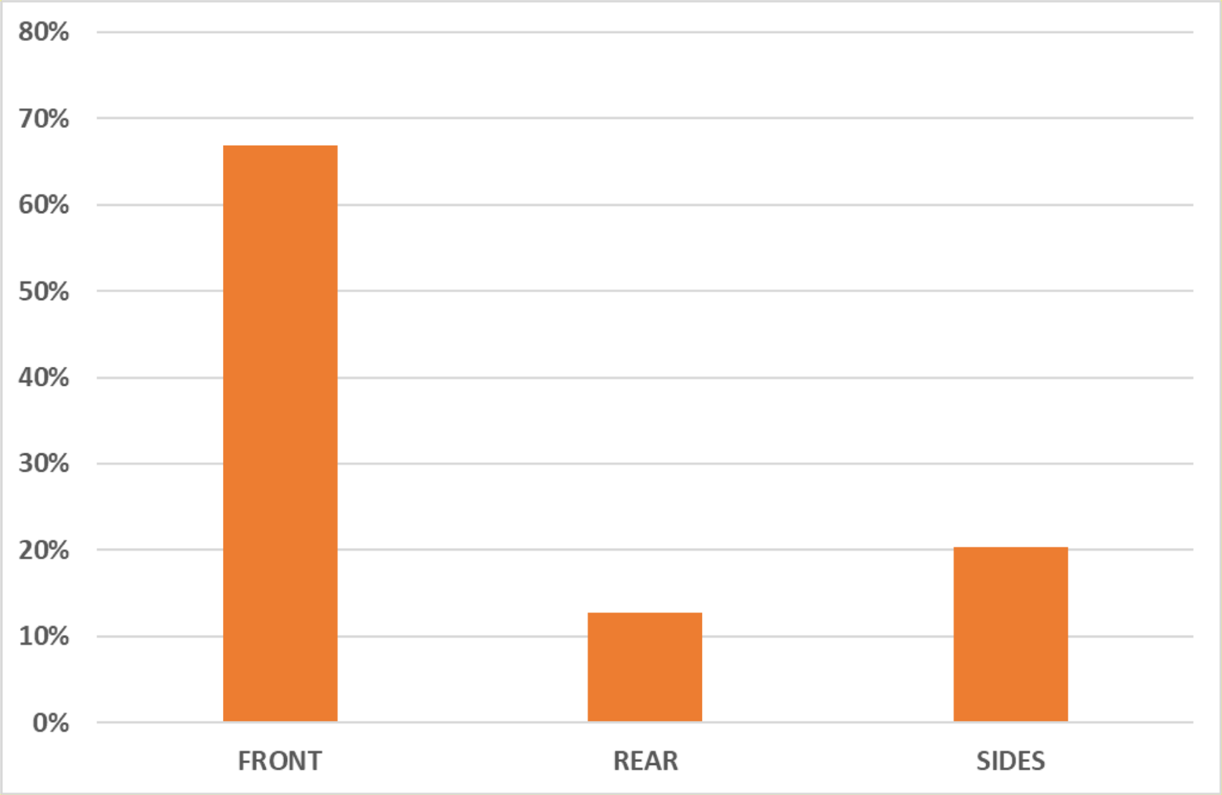

Fig. 1f.

Head impact locations for current study.

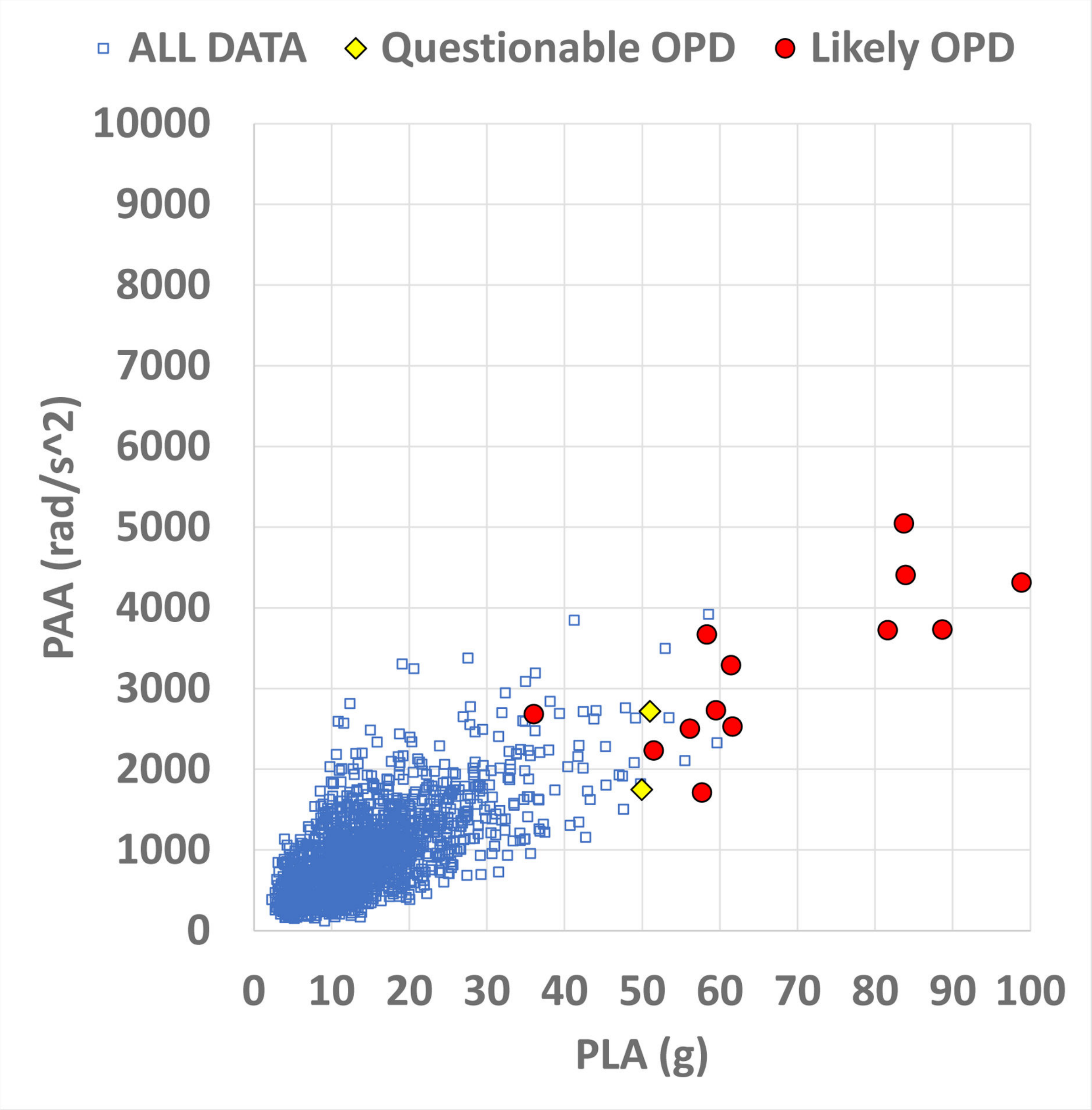

Fig. 2a.

Video-verified impacts (hollow squares) and clinician verified 'Questionable' (filled diamonds) and 'Likely' OPD impacts (filled circles) as quantified by PLA and PAA.

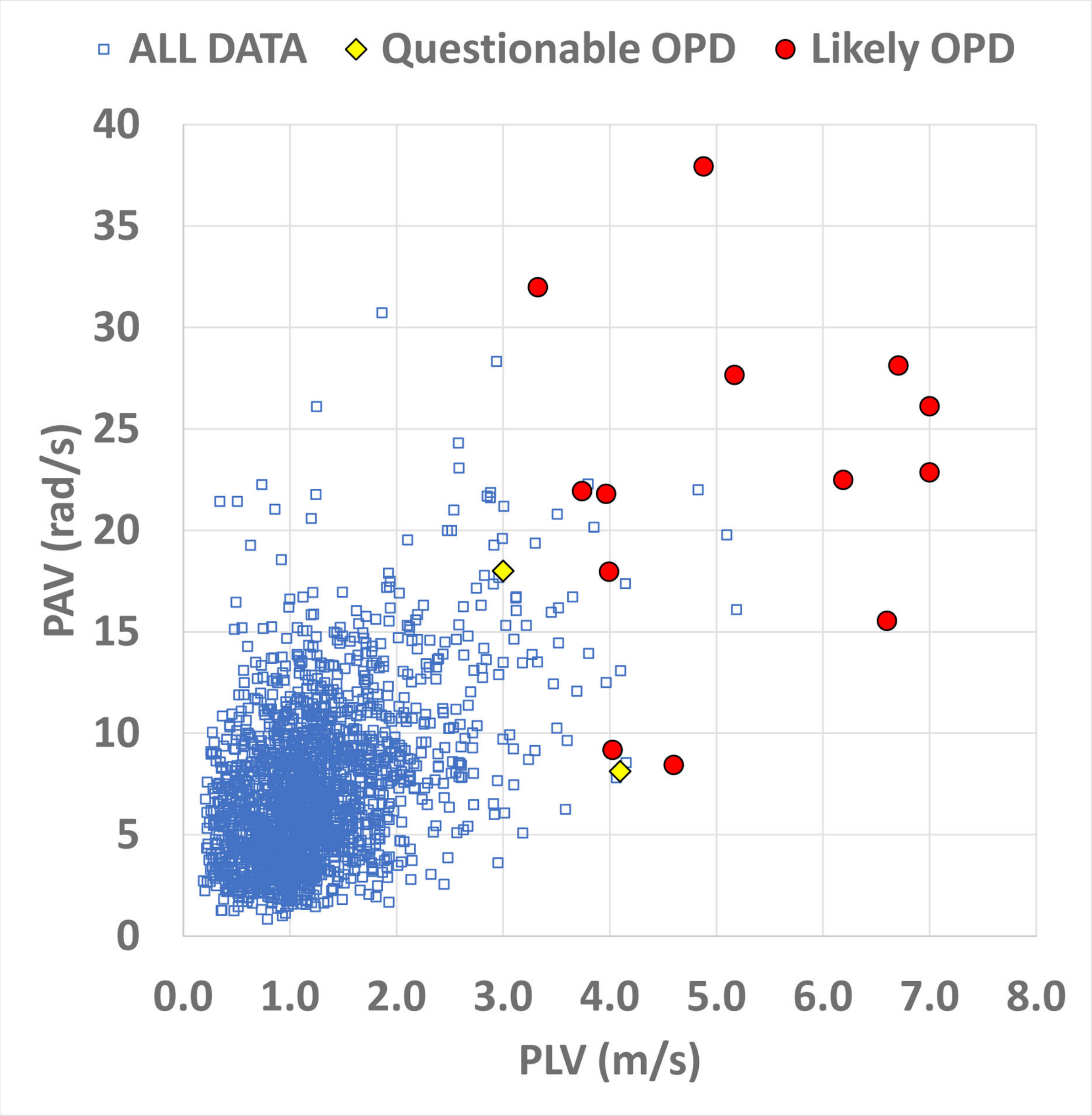

Fig. 2b.

Video-verified impacts (hollow squares) and clinician verified Questionable (filled diamonds) and Likely OPD impacts (filled circles) as quantified by PLV and PAV.

Table 1.

Summary of top 30 head impacts by PLV with OPD observations from video. Non-clinician reviewers identified impacts as OPD or No OPD. An additional 2295 impacts were also classified by video reviewers as No OPD.

	Reviewer #1	Reviewer #2	Clinician Review
No OPD	16	15	15
Questionable OPD	N/A	N/A	2
Likely OPD	14	15	13

Table 2.

Kinematic summary of Clinician Reviewed impacts. Twelve of thirteen (92%) Likely OPD cases occurred to the side and rear of the head.

		Median					
	Clinician Review	**PLA**	**PAA**	**PLV**	**PAV**	**KET**	**Direction**
No OPD	15	47	2100	4.0	16	38	3 SIDE, 1 REAR, 11 FRONT
Questionable OPD	2	50	2200	3.5	13	32	2 SIDE
Likely OPD	13	61	3300	4.9	22	68	8 SIDE, 4 REAR, 1 FRONT