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Characteristics of potential concussive events in elite hurling: a video-analysis study

Mario P Rotundo^{1,2} · Darek Sokol-Randell^{1,3} · Chris Bleakley¹ · Paul Donnelly¹ · Gregory Tierney¹

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Abstract

Background High-impact sports such as hurling place participants at risk of sport-related concussion (SRC).

Aims This study will evaluate the characteristics of potential concussive events (PCEs) that occur in elite male hurling to acquire an understanding of how they occur.

Methods The authors recorded PCEs and their characteristics throughout two seasons of inter-county GAA competition using broadcast footage based on a previously validated protocol.

Results A total of 183 PCEs were identified over 82 inter-county matches (2.23 per match; 59.5 per 1000 h of exposure). PCEs that occurred in the 4th quarter were significantly more likely to result in signs of SRC. Players most often intended to receive/control the sliotar (36.4%, $n=64$) prior to PCEs. The most frequently observed mechanism was shoulder-to-head (20.2%, $n=37$). Impacts to the lateral aspect of the head were 2.7 times more likely to result in visible signs than impacts to anteroposterior regions.

Conclusions Players appear to be at a higher risk of SRC later in the match or when receiving the sliotar. Strikes to the lateral aspect of the head and those involving the shoulder appear to produce severe events. These findings provide initial guidance for the development of targeted player protection strategies.

Keywords Gaelic Athletic Association · Hurling · Sport-related concussion · Video analysis

Introduction

SRC has recently been identified as a major public health concern in high-impact sports [1]. There are concerns surrounding the link between repeated mild traumatic brain injury and neurodegenerative disease such as CTE and Alzheimer's disease [2–4]. While steps have been taken to combat this issue in various professional leagues, amateur and less globalized sporting associations may have fallen behind. The Gaelic Athletic Association (GAA) is the largest sporting body in Ireland and among the most highly regarded amateur sporting organizations in the world. The

GAA presides over numerous sports and plays an influential role in preserving core values of Irish culture [5]. One of the most popular sports under the GAA's purview is hurling, a game inscribed on UNESCO's representative list of intangible cultural heritage of humanity [6].

Hurling is a game played between teams of 15 players and is often referred to as the fastest field sport on earth [7–9]. Players are required to wear helmets with full metal faceguards while using a wooden/composite hurling stick (hurley) to advance a small, hard leather ball (sliotar) down the pitch to score against an opposing team. The sliotar can be caught in the hand and carried for up to four steps, struck in the air, or struck on the ground with the hurley. To carry the sliotar for more than four steps, the player must balance or repeatedly bounce the sliotar on their hurley. This requires remarkable hand–eye coordination at high speeds as players advance the sliotar down the pitch and strike it either between the uprights or into the goal. While outright tackling is not permitted in sports such as rugby, shoulder-to-shoulder contact is encouraged, and high-velocity collisions are commonplace [10, 11]. Players also frequently use

✉ Mario P Rotundo
Rotundo-M@ulster.ac.uk

¹ Sport and Exercise Science Research Institute, Ulster University, Belfast, UK

² Department of Family Practice, University of British Columbia, Vancouver, Canada

³ Department of Neurology, Memorial University of Newfoundland, St John's, Canada

their hurleys to block and hook opponents to gain possession of the sliotar for their team.

We previously published a video-analysis study on the medical assessment of potential concussions in hurling. This study, using the same dataset, identified 183 PCEs over 82 matches, suggesting that head strikes are quite commonplace [12]. Surveys of GAA athletes have also suggested a high burden of SRC and insufficient management of these injuries [13]. Various steps have been taken to improve concussion assessment practices, such as the implementation of the GAA concussion management guidelines and, more recently, the announcement of a concussion interchange rule [14]. We have discussed this in previous papers on both Gaelic football and hurling [12, 15]. However, these measures do little to reduce the primary incidence or severity of concussion. Elucidating the characteristics and circumstances under which PCEs occur may allow us to establish targets for future research and player protection strategies [16]. This study intends to describe the characteristics of PCEs that occurred in national league and championship inter-county hurling over two playing seasons. The number of visible concussion signs present on video analysis will serve as a proxy for PCE severity and will be used to suggest which characteristics might be more likely to result in SRC. The results will then be interpreted to determine patterns and possible player protection strategies to be considered by the league.

Methods

Video incident analysis has been demonstrated to be a valid method of analyzing situational factors, mechanisms, and signs of injury related to SRC. [17–20] We have previously used and reported a similar methodology for video analysis in Gaelic football and soccer. [16, 21] Consistent with prior work, a PCE is defined as any event in which a player is unable to resume play in a meaningful capacity within 5 s of direct and visible head contact [15, 21]. In other words, the player was either down on the ground, staggering, or otherwise disengaged from the play, therefore not participating purposefully or efficaciously in the gameplay around them. It is important to note that the term PCE is not synonymous with SRC; PCEs include a broad spectrum of head impacts that may or may not lead to a clinical diagnosis. Ambiguous events were excluded, such as those involving play-acting, questionable head contact, or minor contact where the blow could not possibly produce a concussive force. Play-acting was defined as a player appearing to take a dive or embellish an injury with the intention to gain a foul for his team. Although theoretically any contact to the head or body has the potential to cause concussion, we used our better

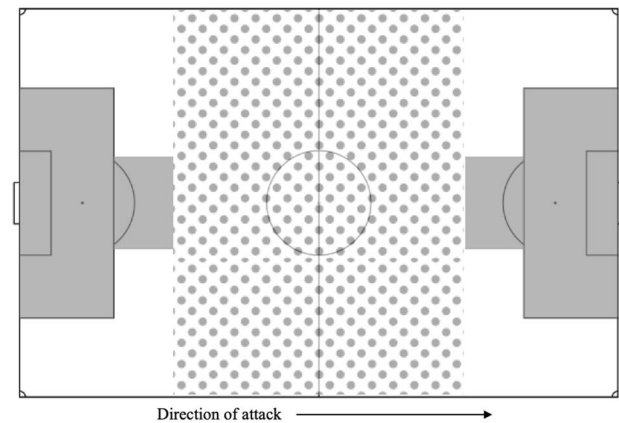


Fig. 1 Recorded regions of the field where PCEs occurred including center (spotted), wings (white), and goal (gray)

judgment to exclude such contacts as finger grazes or events that did not produce any recoil, artifact, or reaction from the player whatsoever. To exclude a suspicious event, both reviewers had to agree upon the decision.

Reviewers were trained in video analysis at the injury prevention lab at St Michael's Hospital in Toronto, Ontario, Canada, and have previously published PCE research in international soccer and Gaelic football. [12, 15, 16, 21, 22] Match footage was retrieved from the GAAGO online streaming service and was analyzed using QuickTime Player v10.5 (which enables frame-by-frame viewing). No patient data was utilized for this study, and all footage is public domain. Reviewers were permitted to rewatch and pan the footage at their discretion. In player-to-player contact, we defined “player 1” (P1) as the player who sustained head contact and “player 2” (P2) as an involved player who did not. If both players sustained head contact during a PCE, P1 was defined as the one who was assessed for a longer period, although both cases were still recorded as PCEs. Reviewers ascertained the time, context, intent of player, and area of the field where the PCE occurred (Fig. 1), as well as the mechanism and location of the impact (Fig. 2). Reviewers recorded whether the player appeared to anticipate the impending impact. The definition of anticipation was based on one previously established in rugby research,

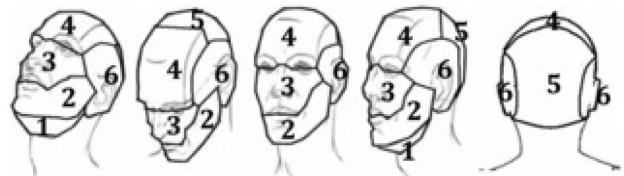


Fig. 2 Recorded regions of head impact location involved in PCEs. These include (1) sub-mandibular, (2) mandibular, (3) maxillary, (4) frontal, (5) parieto-occipital, and (6) temporal

which classified the following as anticipated impacts: (i) player initiated the impact himself, (ii) player physically braces himself prior to impact, and (iii) player noted to visibly observe the impending impact [23]. Finally, consistent with our prior work and a recent international consensus statement, reviewers searched for the visible signs of concussion that are thought to be the most predictive of concussion has occurred. The presence of any one of these signs necessitates the immediate removal of an athlete from play, pending a professional assessment. [24] As mentioned in our introduction, these signs were used as a proxy for PCE severity in our analysis. When we refer to severe PCEs, we are referring to those that produced one or more visible signs of concussion and are therefore theoretically more

likely to have resulted in true SRC. The complete analysis protocol is summarized in Table 1.

Prior to analysis taking place, an inter-rater reliability test was performed. Each reviewer independently viewed five hurling matches and identified PCEs based on the criteria above, recording the exact minute of each incident. Next, each reviewer independently analyzed approximately 30 PCEs identified from exhibition and All-Ireland club matches (not included in data analysis) using the adapted PCE analysis spreadsheet. All discrepancies from the inter-rater reliability were discussed and clarified based on our comprehensive definitions. When a favorable result was achieved, reviewers independently identified PCEs throughout 59 and 52 matches of the 2018 and 2019 GAA National Hurling League

Table 1 Summary of peri-PCE characteristics analysis

<i>Pre-PCE</i>	<i>Mid-PCE</i>	<i>Post-PCE</i>
<p>Intent before injury (P1) Action of P1 prior to injury</p> <ul style="list-style-type: none"> • Carry • Receive/control • Challenge • Shoot • Pass • Malicious action • Block • Other <p>Preceding event Event occurring just prior to PCE</p> <ul style="list-style-type: none"> • Free • Puck-out • 45 • Sideline cut • Short pass • Long pass • Interception • Carry • Shot attempt • Bunch-up <p>Time quarter</p> <ul style="list-style-type: none"> • 1/2/3/4 	<p>PCE context Context under which PCE occurred</p> <ul style="list-style-type: none"> • Hurley tackle • Aerial battle • Body tackle • Ground ball • Other <p>Mechanism Cause of strike leading to PCE</p> <ul style="list-style-type: none"> • Head • Hand/fist • Shoulder • Elbow • Arm • Leg/hip • Knee • Foot/shin • Post • Ground • Hurley • Chest/back • Other <p>Impact region Region of head affected by impact</p> <ul style="list-style-type: none"> • Sub-mandibular • Mandibular • Maxillary • Frontal • Occipital • Parieto-temporal • Not visible 	<p>Card Card awarded on play?</p> <ul style="list-style-type: none"> • Yellow • Red • Black <p>Foul awarded?</p> <ul style="list-style-type: none"> • Y/N <p>Second hit 2nd strike within 2 s of 1° impact</p> <ul style="list-style-type: none"> • Y/N <p>Anticipation Did player appear to expect impact?</p> <ul style="list-style-type: none"> • Y/N <p>Visible signs of concussion</p> <ul style="list-style-type: none"> Lying motionless Motor incoordination—ataxia Impact seizure Tonic posturing No protective action—floppy Vacant look

inter-county seasons and championships, respectively. Each PCE was evaluated based on the parameters outlined above, and data were recorded for statistical analysis. Reviewers consulted each other and collaborated if any questions or difficulties arose during the analysis.

Data analysis

Descriptive statistics were reported as means, counts, or frequencies and their associated percentages. A raw agreement and Cohen's kappa coefficient were calculated for the inter-rater reliability test. Frequency distributions were used to examine patterns of PCEs based on time-quarter, context, anticipation, field region, mechanism, and impact location. A series of chi-squared tests were then performed to search for an association between these categorical variables and PCE severity (no signs vs. one or more visible signs of concussion). All expected cell counts must have been > 1 , and no more than 20% of expected counts were < 5 [25]. If a contingency table violated this assumption, categories within a variable were combined logically and based on author consensus. For example, in our analysis of impact location, the mandibular and temporal regions were combined into lateral aspect of the head, and the frontal, maxillary, and occipital regions were combined into the anteroposterior regions.

When omnibus chi-square statistics were statistically significant ($p < 0.05$), we examined individual cell contributions using their residuals (difference between the observed (O) and expected values (E) for a cell), standardized to a z score [standardized residual = $(O - E)/\sqrt{E}$]. If applicable, we also compared cells of greatest interest using odd ratios ($\pm 95\%$ confidence intervals). We used log-linear tests to explore potentially important three-way interactions between sets of categorical variables and PCE severity.

Results

Inter-rater

Raw agreement was 100.0% for the identification of PCEs. A Cohen's kappa was not calculated for identification of PCEs because the probability that both reviewers would record the same minute by chance is negligible. For the PCE analysis spreadsheet, raw agreement was 96.5% and Cohen's kappa coefficient was 0.83 (95% CI 0.799 to 0.861) [26]. A Cohen's kappa value greater than 0.8 is indicative of almost perfect agreement [27].

Incidence

Throughout the 2018 and 2019 GAA inter-county hurling season, we identified a total of 176 incidents over 82 matches. Seven of these involved both P1 and P2 sustaining a PCE,

Table 2 PCEs per quarter of match, by number of concussion signs observed (%)

Time quarter	0	1+	Total
1	31 (86.1)	5 (13.9)	36 (19.7)
2	46 (83.6)	9 (16.4)	55 (30.1)
3	35 (81.4)	8 (18.6)	43 (23.5)
4	28 (57.1)	21 (42.6)	49 (26.8)
Total	140 (76.5)	43 (23.5)	183 (100.0)

resulting in 183 PCEs (2.2 per match; 59.5 per 1000 match hours of exposure).

Game circumstances

We observed that 36 (19.7%) PCEs occurred in the first quarter of the match, 55 (30.1%) in the second quarter, 43 (23.5%) in the third quarter, and 49 (26.8%) in the fourth (Table 2). There was a significant association detected between the number of visible signs and match quarter, $\chi^2(3, n = 183) = 13.95, p = 0.0002$. Posthoc testing confirmed the number of PCEs with at least 1 visible sign was significantly higher than expected in the 4th quarter of the match, based on a standardized cell residual of +2.8. The greatest difference was found between the start vs the end of the match, with severe PCE being four and half times more likely to occur in the last quarter compared to the 1st quarter of play (OR 4.6 95% Cis 1.54 to 13.98).

Impact location

The mandibular region was the most impacted region, with 57 (31.2%) PCEs. Impacts to the frontal and temporal regions comprised 42 (23.0%) and 38 (20.8%) PCEs, respectively (Fig. 3). There was a significant association between impacted region and visible signs of concussion, $\chi^2(2, n = 183) = 7.19, p = 0.03$. Post hoc tests found a higher-than-expected frequency of concussion signs associated with impacts to the

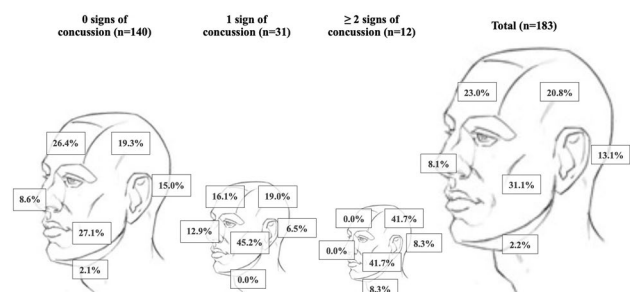


Fig. 3 Percentage of PCEs affecting each region of the head, stratified by number of concussion signs produced

lateral aspect of the head (mandibular/temporal) (standardized cell residual of +1.6). Impacts to this region were 2.7 times more likely to result in severe PCEs compared to impacts involving the anteroposterior regions (frontal/maxillary/occipital) of the head (ORs 2.7 95% Cis 1.3–5.7, $p=0.0096$).

Mechanism

When similar mechanisms were grouped together, the most common were shoulder to head ($n=37$, 20.2%) and hurley to head ($n=35$, 19.1%), followed by upper extremity ($n=49$, 26.8%), head to head ($n=23$, 12.6%), and lower extremity ($n=21$, 11.5%). Shoulder-to-head impacts produced visible signs of concussion in 14 (37.8%) cases and head-to-head impacts in 8 (34.8%), compared to 3 (8.6%) in hurley-to-head impacts. This data is represented in Fig. 4.

The omnibus χ^2 statistic was not significant between mechanism and visible signs, $\chi^2(5, n=183)=10.7, p=0.06$. However, post hoc tests found a higher-than-expected number of PCEs with visible signs due to shoulder-to-head impacts ($z=1.8$). This mechanism was 6.5 times more likely to result in PCE with visible signs compared to hurley-to-head contact (OR 6.49, 95% Cis 1.67–25.22, $p=0.007$). Head-to-head impacts were also more likely to produce visible signs compared to hurley to head (OR 5.68, 95% Cis 1.32–24.54, $p=0.019$).

Number of Concussion Signs by Mechanism

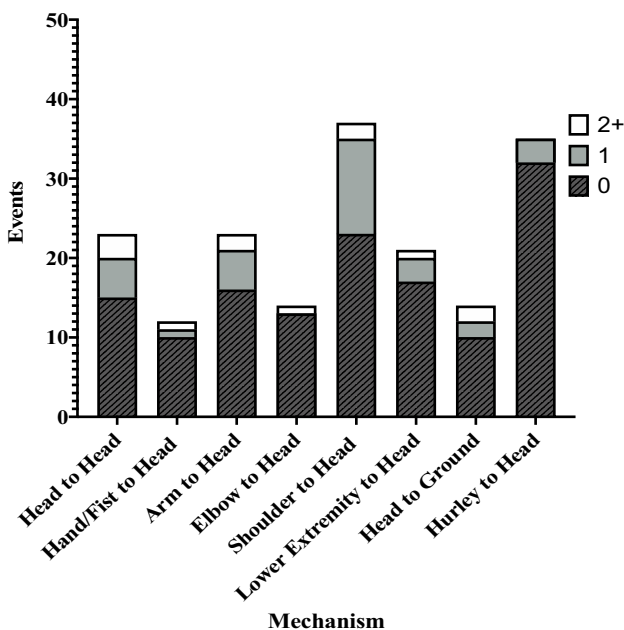


Fig. 4 Number of concussive signs displayed, by mechanism of injury

Variable interactions

Taken together, 26 PCEs involved shoulder-to-mandible collisions (14.2%), 12 (46.2%) of which resulted in one or more visible signs of concussion. There was a clear association between impact location and PCE mechanism, $\chi^2(8, n=183)=39.79, p<0.0001$. Our post hoc tests determined that most impacts to lateral aspect of the head were caused by an opponent’s head or shoulder (43.6%, 43/95; z score = +2.1), whereas impacts to the anteroposterior regions of the head were primarily caused by the hurley stick (34.1%, 28/82, z score +3.1). We included both variables (impact location and mechanism) in a three-way log-linear analysis alongside injury severity, but the highest order interaction (impact location \times mechanism \times visible signs) was nonsignificant $\chi^2(8, n=183)=3.36, p=0.910$.

Player intent and pitch-related factors

For P1, the most common player intent preceding an incident was attempting to receive/control the sliotar (36.4%, $n=64$), carrying the sliotar (31.3%, $n=55$), and delivering a challenge (15.9%, $n=28$). For P2, the most common intent was delivering a challenge (76.1%, $n=134$). Detailed player intent data by pitch region and visible signs are displayed in Table 3.

PCEs occurred with a similar frequency in the center and goal regions of the pitch. This data is displayed in Fig. 5. The most common contexts during which PCE occurred were body tackles (44.3%, $n=78$), ground balls (24.4%, $n=43$), and hurley tackles (18.2%, $n=32$). PCE context data stratified by field region is displayed in Table 4. Seventy-seven (42.1%) players did not anticipate the impending impact that resulted in a PCE. There was a significant association detected between intent and anticipation ($\chi^2(6, n=176)=22.53, p<0.001$). Post hoc analysis revealed that when P1 intended to carry the ball, he was significantly more likely to anticipate a PCE. Unanticipated events were underrepresented during a carry ($z=-2.4$), and players receiving/controlling the sliotar were 4 times less likely to anticipate an impending impact than in the event of a carry. (ORs 4.1 95% Cis 1.8–9.1, $p=0.0007$).

Concussion signs

Of 183 PCEs, concussion signs were present in 43 (23.5%) cases. Two or more signs were present in 12 cases (6.6%) and three or more in 6 cases (3.3%). Lying motionless ($n=21$) and blank/vacant look ($n=18$) were the most common signs, followed by motor incoordination ($n=16$).

Table 3 Intent prior to injury of both P1 and P2, by region and signs (%)

Intent before INJ	Pitch region						Signs							
	P1			P2			P1			P2				
	Center	Goal	Wing	TOTAL (%)	Center	Goal	Wing	TOTAL	0	I +	TOTAL	0	I +	TOTAL
Carry	19	29	7	55 (31.3)	3	3	3	9 (5.1)	44	11	55 (31.3)	0	0	0
Receive/control	28	19	17	64 (36.4)	11	5	2	18 (10.2)	49	15	64 (36.4)	2	0	2 (28.6)
Challenge	11	12	5	28 (15.9)	51	55	28	134 (76.1)	22	6	28 (15.9)	3	1	4 (57.1)
Shoot	3	1	0	4 (2.3)	1	2	0	3 (1.7)	2	2	4 (2.3)	0	0	0
Pass	7	4	5	16 (9.1)	1	1	0	2 (1.1)	12	4	16 (9.1)	0	0	0
Malicious	0	0	0	0 (0.0)	3	0	0	3 (1.7)	0	0	0 (0.0)	0	0	0
Block	1	2	0	3 (1.7)	0	0	0	0 (0.0)	1	2	3 (1.7)	0	0	0
Other	3	3	0	6 (3.4)	2	4	1	7 (4.0)	4	2	6 (3.4)	1	0	1 (14.3)
Total (%)	72 (40.9)	70 (39.8)	34 (19.3)	176 (100.0)	72 (40.9)	70 (39.8)	34 (19.3)	176 (100.0)	134 (73.2)	42 (23.0)	176 (96.2)	6 (3.3)	1 (0.55)	7 (3.8)

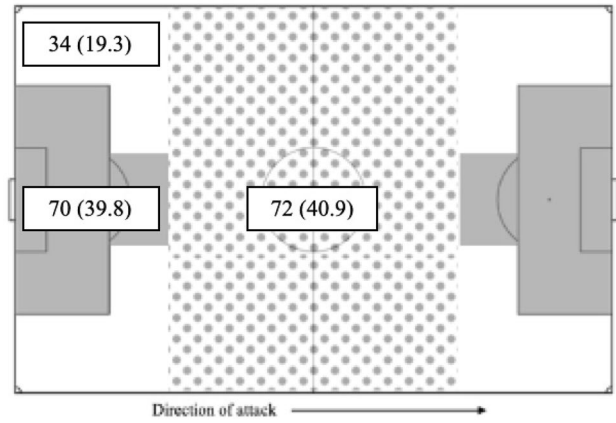


Fig. 5 PCE incidents stratified by field region (%)

Discussion

Previous literature has reported 0.19–0.23 head injuries per 1000 h of hurling [28, 29], and various studies have indicated that head/neck injuries only account for 2.0–4.0% of injuries [28, 29]. Although a PCE does not necessarily indicate that a concussion has occurred, at 59.5 PCEs per 1000 match hours, our findings would suggest that there is a much higher incidence of concussion in hurling than is perhaps estimated.

PCEs were distributed relatively evenly throughout matches. However, 42.9% ($n = 21$) of PCEs occurring in the 4th quarter produced visible signs of concussion, representing a significantly higher-than-expected frequency than other quarters (Table 2). Our data suggests that severe PCEs were 4.5 times more likely to occur in the final quarter compared to the first. There are several possible reasons why this might be the case. First, it is possible that players are more prone to excessive aggression and impulsivity with prolonged physical exertion and as the game draws to a close [30], as has been demonstrated in ice hockey [31, 32]. Although our study only identified three instances of blatant malicious intent that led to PCE, all of these events occurred in the latter half of the match. Second, players may become more fatigued as the game progresses. GPS data demonstrates that mean total distance covered by hurlers is relatively consistent throughout a match. However, high-speed running distance and high-metabolic load distance (a figure combining HSR distance as well as acceleration/decelerations) tend to decrease quarter-by-quarter across all positions. Midfielders and half-forwards, who covered the most total distance and sprint distance in Q1, respectively, experienced the most profound reductions, suggesting that fatigue is a factor as the match progresses [33]. It is thought that physical resilience and tackle technique deteriorate with fatigue as players absorb numerous hits, leading to elevated

Table 4 PCE context stratified by pitch region (%)

<i>Pitch region</i>	<i>PCE context</i>					Total
	Hurley tackle	Aerial battle	Body tackle	Ground ball	Other	
Center	19 (26.4)	9 (12.5)	28 (38.9)	14 (19.4)	2 (27.8)	72 (40.9)
Goal	9 (12.6)	4 (5.7)	38 (54.3)	14 (20.0)	5 (7.1)	70 (39.8)
Wing	4 (11.8)	2 (5.9)	12 (35.3)	15 (44.1)	1 (2.9)	34 (19.3)
Total	32 (18.2)	15 (8.5)	78 (44.3)	43 (24.4)	8 (4.5)	176 (100.0)

susceptibility to head injury in the later stages of a match [34, 35]. This is consistent with studies in rugby and ice hockey, which detected a correlation between fatigue and elevated risk of concussion [36, 37]. Fatigued muscles are less able to absorb energy and, as a result, are likely more susceptible to injury.[38, 39] Although more research is needed to verify this, it is thought that the musculature of the neck plays an important role in neutralizing forces to the head, and neck strength has shown a significant inverse correlation with concussion risk [40, 41]. In rugby, tackling competency appears to decrease with increasing fatigue in sub-elite players [42] and the number of tackles a player is involved in has been positively correlated with markers of muscle damage [43, 44]. The combination of fatigued muscles and a commensurate decrease in tackle technique may explain why severe PCEs tended to occur later in the game.

PCE context is a parameter used to generate a general understanding of how PCEs occur. In most cases, defending players choose to either swing their hurley at an opponent to knock the sliotar from their possession (18.2%) or use a body tackle to knock their opponent off balance (44.3%). When organized by pitch region, body tackles were found to frequently occur in the goal region and hurley tackles in the center region of the pitch. Given the strategic importance of the goal region, it is reasonable to suggest that players are inclined to be more physical here, as has been similarly described in both Gaelic football and professional soccer [16, 21]. When we stratify context by intent, most PCEs (52.7%) occurring in the goal region involved P1 attempting to carry the sliotar, versus receive/control, which preceded only 29.7% ($n = 19$) PCEs in the goal region. Players will opt to carry the sliotar into the goal region if they are attempting to score on goal, rendering them more exposed to body tackles, while passes and puck-outs are most often received in the center and wing regions and tend to draw hurley tackles (Table 4).

Shoulder-to-head was the most common mechanism (20.2%, $n = 37$) and produced significantly more severe PCEs than expected ($z = 1.8$) (Fig. 5). While hurley-to-head was a comparably common mechanism (19.1%, $n = 35$), shoulder-to-head impacts were 6.5 times more likely to result in a severe PCE. To explain this phenomenon, we searched for an association between mechanism and impact location. Impacts to the lateral aspect of the head were

most often caused by an opponent's head/shoulder (43.6%, 43/95; z score = 2.1), whereas impacts to the anteroposterior regions of the head were primarily caused by the hurley stick (34.1%, 28/82, z score = 3.1). The lack of significant interaction between impact location, mechanism, and visible signs in a three-way log-linear analysis suggests that the strong association between impact location and PCE severity is not affected by underlying mechanism. For the purposes of player protection, it is helpful to know that shoulders tend to produce severe PCEs. This raises an important question: are shoulder-to-head impacts more dangerous due to the region of the head that they tend to affect?

Similar to what we found in Gaelic football, it appears that when players are distracted, they are rendered susceptible to unanticipated “blind-side” collisions from approaching defenders [16]. We found that hurlers intending to receive or control the sliotar prior to when a PCE occurred were 4 times less likely to anticipate the impending collision compared to a player carrying the sliotar. Across multiple contact sports, unanticipated collisions have been recognized as a risk factor for SRC [16, 45–49]. When a player is looking away or unaware of an incoming tackle, important biomechanical implications for concussion risk may come into play. For one, the lateral aspect of the head may be rendered vulnerable. The brain is resistant to changes in volume but has limited resilience against changes in shape [50]. On impact, the brain tends to deform in shear (Fig. 6) [51], rendering it more sensitive to rotational loads [51, 52]. According to several studies, rotational loads produce more diffuse damage and relative brain motion than linear forces [53, 54], and impacts to the lateral aspect of the head appear to produce increased rotational forces and damage to the brain [55–57]. This effect may be compounded if the player does not anticipate the impending collision, as he cannot tense the musculature of the head and neck to absorb the impact [58–60]. This might explain why blows to the lateral aspect of the head were more likely to produce severe PCEs. It might also suggest why shoulder-to-head impacts, which were significantly more likely to affect the lateral aspect of the head, were significantly associated with severe PCEs. However, the exact causative mechanism of concussion remains quite contentious, and we can only speculate here as to why these results occurred.

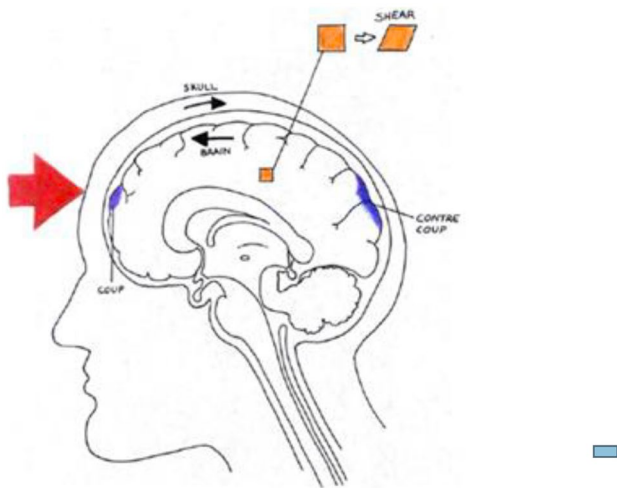


Fig. 6 Forces on the brain during impact, including the coup-conter coup and shear mechanisms [51]

Implications

Hurling is an extremely fast-paced and physical sport that demands remarkable hand–eye coordination and attentiveness to the small and elusive sliotar, under the constant constraints of space and time. Based on the prevalence of PCEs and visible signs of concussion that we recorded over two seasons, it is reasonable to suggest that elite hurlers are at an elevated risk of concussion. This underscores the importance of identifying trends such as those discussed in this study to offer pointed suggestions on how to effectively reduce the incidence and severity of PCEs in hurling. It is worth noting the utility of video-analysis in this regard, and we continue to advocate for its usage for PCE surveillance and review, similar to what has been done in other sports [18, 61–63].

Given that PCEs tend to be more severe in the final quarter of the match, it is important that referees keep the game under control. The league might consider offering more substitutions to managers in the second half or allow a longer half-time to preserve tackle technique and resilience as the battle wears on. Adding neck strengthening protocols and emphasizing tackle technique in training may also be beneficial, as has been attempted with some success in rugby and American football, respectively [64, 65].

Our data suggests that player attention to incoming tackles is of paramount importance. PCEs tend to occur in situations where the player’s attention is diverted in some way, whether it be receiving or controlling a pass or attempting to corral a ground ball. These situations set the stage for blind-side strikes to the lateral aspect of the head, which as we explained above, can be extremely dangerous. We continue to advocate for severe penalties, suspensions, and fines for blind-side hits to the head, regardless of intent, to

encourage players to be more deliberate and controlled with their tackles, especially when it may affect their team’s success. Variations of such interventions have been effectively integrated in the National Hockey League and National Football League regarding blind-side hits [47, 48, 66]. We have discussed this in more depth in our prior work [16].

Finally, stakeholder education with regard to concussion awareness, tackling technique, and protective strategies should be emphasized [67, 68]. Players should be taught from an early age that hits to the head, especially from the side on an unsuspecting opponent, can cause severe brain injury. Referees might approach high-risk situations with a heightened awareness and have a lower threshold for issuing fouls and cards if necessary. In training, coaches should emphasize “heads up” play and situational awareness, especially when receiving a pass in the center of the pitch or when carrying the sliotar into the face of the goal. The aptly named “heads up” style of play has been a fixture in ice hockey coaching for many years, which fortunately provides an existing framework that could likely be adapted to hurling [69–71].

Limitations

The reviewers in this study were unable to control the movement of the camera, image quality, resolution of the athlete of interest, and angles available. This can influence the quality of the data collected. Some data points were difficult to assess in hurling compared to un-helmeted sports, such as anticipation and “vacant look.” However, most players removed their helmet after suffering a PCE, which mitigated this somewhat.

As explained in the methods, a PCE is not synonymous with SRC. PCEs include a broad spectrum of head impacts that may or may not lead to a clinical diagnosis. Despite a visible blow to the head, there is a possibility that players who subsequently disengaged from the play did so for a different reason, such as a coincident injury that we may have missed, leading us to overestimate the number of PCEs.

The hypothesis that PCEs were significantly more likely to occur in the 4th quarter of the match due to fatigue is limited by our failure to collect data on player substitutions. It is possible that some of the PCEs we noted to occur in the 4th quarter happened to players who entered the game later in the match. We were unable to find a reliable source for this data after the fact. Future research should take this into account.

Although a recent consensus study concluded that the six video signs of concussion used in this study are highly predictive of a concussion has occurred [24], reliance on video signs to predict a clinical diagnosis remains precarious. The identification of the signs of concussion relies on the

reviewer's interpretation of written definitions, introducing an element of subjectivity to this research. Furthermore, to our knowledge, the signs used in this study have not yet been validated based on clinical data, and not all SRCs present clinical signs on video. One study conducted on National Hockey League players showed that 53.0% of clinical concussions did not produce visual signs [72]. However, the signs in this study were only used as a proxy measurement for PCE severity and were only intended to suggest a higher probability of a concussion has occurred. For an event to qualify as a PCE, to begin with, the player had to suffer a direct, visible impact to the head and disengage from the play for 5 s or more. If we assume that approximately half of concussions present with visual signs, it is possible that this study drastically underestimated the number of PCEs that could be classified as severe. Unfortunately, we had no access to medical reports from the games, making it impossible for us to infer which PCEs were associated with clinical concussions. Statistically, the value of the three-way log-linear analysis between impact location, mechanism, and visible signs may have been impacted by the limited variety of mechanisms detected in our study. A more powerful sample would be needed to verify this statistic.

In the future, clinical diagnosis data would be beneficial for validating concussion signs and risk factors. Biomechanical analysis of PCEs, such as using instrumented mouthguards, would also offer valuable quantitative insight into risk factors and characteristics that lead to dangerous forces on the brain [52, 73].

Conclusion

The current study intended to investigate the characteristics of PCEs in national league and championship inter-county hurling. High-risk characteristics were identified in relation to game time, player intent, mechanism, and impact location. For instance, impacts that occur later in the match and affect the lateral aspect of the head appear to produce more severe events. This provides us with a set of preliminary targets for intervention and future research. The league might consider implementing more severe penalties, especially for "blind-side" hits to the lateral aspect of the head, to encourage players to be more deliberate with their tackles. Compulsory concussion education offered to players and managers could raise awareness of high-risk situations and emphasize good tackling technique and heads-up play. Given the usefulness of video analysis demonstrated by our research, we continue to recommend that it be used for SRC surveillance, review, and future research. Inter-county hurling represents the highest caliber competition in the sport, and we are optimistic that targeted player protection strategies will meaningfully reduce the risk of concussion at all levels of the

game without affecting pace and intensity. Ultimately, it is in everyone's interest to keep talented young athletes healthy and active throughout their careers and beyond.

Declarations

Conflict of interest The authors declare no competing interests.

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