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applied sciences

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Heads Up! A Biomechanical Pilot Investigation of Soccer Heading Using Instrumented Mouthguards (iMGs)

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Abstract: Soccer players purposefully head the ball, raising concerns about reduced tolerance to concussion and potential long-term brain health. By combining qualitative video analysis with custom-fit instrumented mouthguards (iMGs), we aimed to categorize header kinematics (peak linear acceleration (PLA) and peak angular acceleration (PAA)) by header type and ball delivery method. iMGs were fitted to 10 male collegiate players for twelve matches. A total of 133 headers were verified and contextualized via video review. The most common header type (38.7%), as well as the preceding ball delivery method (47.4%), was found to be a pass. Approximately one-quarter of header impacts (27.0%) occurred below 10 g. For header type, there were no significant differences in kinematics, with shot attempts having the highest median PLA and PAA. For ball delivery methods, goal kicks had significantly greater PAA than long balls and pass attempts. The current study highlights the utility of qualitative video analysis in combination with real-time head kinematic data from iMGs to understand the mechanism and severity of header impacts. The pilot findings indicate that high-speed ball delivery methods result in higher head kinematics and should be a focus of future mitigation strategies.

Keywords: biomechanics; heading; football; concussion; head impacts; head acceleration events

Citation: Sokol-Randell, D.; Stelzer-Hiller, O.W.; Allan, D.; Tierney, G. Heads Up! A Biomechanical Pilot Investigation of Soccer Heading Using Instrumented Mouthguards (iMGs). *Appl. Sci.* **2023**, *13*, 2639. https://doi.org/10.3390/app13042639

Academic Editors: Enrique Navarro, Santiago Veiga and Alejandro San Juan Ferrer

Received: 31 January 2023
Revised: 15 February 2023
Accepted: 15 February 2023
Published: 18 February 2023

1. Introduction

Analysis of the incidence, mechanism and severity of heading in football is needed to understand the extent of the relationships between heading and potential risks of neurodegenerative diseases. Soccer poses a unique concern for concussion injury and repetitive head acceleration events (HAEs) [1]. It is the only sport in which players purposefully use their unprotected head (termed header) to play the ball for both offensive and defensive purposes [2]. Being the most widely played sport in the world [3], soccer generates a large number of head injuries worldwide [4]. Currently, player-to-player contact represents the most common mechanism of concussion [5].; however, it only accounts for a small minority of the total HAEs experienced by players [6]. Instead, heading the ball has been identified as representing over 90% of the HAEs experienced in-game [7], with evidence suggesting that continued exposure to repetitive HAEs may dampen an individual's concussion threshold [8], ultimately conferring a risk of brain injury [9].

The incidence of concussions in soccer continues to rise globally [10–12], with heading the ball being implicated in up to a quarter of cranial injury cases [12]. On average, a player is subjected to six or seven heading incidents per game [13–15], with Matser et al. [16] estimating season frequencies well above 800 occurrences in professional players, not including practice sessions. Several studies [17,18] have suggested a dose-response relationship between heading the ball and cognitive impairment, as players experiencing the highest heading frequencies consistently scored the lowest on visual memory and vestibular function testing [17]. However, others remain conflicted, questioning accountability for confounding variables and various methodological shortcomings [12,19–21]. Furthermore, when compounded by inconsistent reporting metrics and a lack of standardized methodology, associations between HAEs and neurocognitive impairment are rendered subjective, deepening uncertainties [1]. Yet, if HAE mitigation or prevention efforts are to be efficacious, it is necessary to have a thorough understanding of the biomechanics and to identify the areas of sports where HAEs occur with the greatest severity.

HAE kinematics (e.g., linear and angular acceleration) are associated with brain injury risk [22]. The primary contributor to brain injury appears to be rotational head motion, and an emerging evidence base illustrates various biomechanical brain injury mechanisms, including those involving repetitive HAEs [22]. HAE kinematics can be measured using wearable head sensors equipped with accelerometers and gyroscopes [23]. Patch devices with these sensors may provide erroneous measurements due to poor skull coupling (soft tissue artifacts), which can result in overestimations of HAE magnitude [24]. Alternatively, instrumented mouthguards (iMGs) have been shown to be more accurate by directly coupling to the upper dentition and thus skull, reducing soft tissue artifacts and making them the preferred choice for measuring HAEs in real-time [24,25]. From this, researchers have identified the penalty box to be a high-risk area for concussive injury, with ball speeds frequently exceeding 120 km/h [26] and peak acceleration exposures to the head 150% greater than those noted in hockey or American football [27]. In response, the Professional Footballers' Association (PFA) has begun trialing heading-restricted matches in which players follow specified heading counts and have designated areas to head the ball [28]. However, officials fear these regulations may hinder heading development programs resulting in improper technique and eventual heightened concussion risk [6]. These proactive approaches notwithstanding, only two studies [1,6] concerning female youth collegiate soccer players have been performed characterizing in-game HAE using instrumented mouthpieces/iMG. As such, the aim of our research was to identify and quantify head kinematics associated with different types of on-field header impacts in men's collegiate soccer. By combining qualitative video analysis with objective kinematic measures, we sought to categorize HAEs by header type, ball delivery method, and field location to inform concussion prevention and HAE mitigation strategies.

2. Materials and Methods

Ten male players were recruited from a university intra-mural football league. Each player provided written consent, which included 2 defenders (center-backs), 5 midfielders (2 defensive, 1 central, and 2 attacking), and 3 forwards (1 striker and 2 wingers). Ethical approval was granted by the Faculty of Biological Sciences Ethical Review Committee at the University of Leeds (#BIOSCI 19-026). All players were male, with a mean age of 20 ($\pm$1) years, a mean weight of 76.2 ($\pm$9.4) kg, and a mean height of 182.2 ($\pm$6.5) cm.

Data were collected from twelve matches within the 2021-2022 season. To be eligible for the study, players had to be active participants during the season, have at least 5 years of experience playing football competitively and have not sustained a concussion in the last year. Prior to the season's commencement, participants underwent dental impressions in order to be outfitted with their custom-fit iMGs (Prevent Biometrics, Minneapolis, MN). iMGs were provided to all athletes prior to each match, and players had the option to decline or remove the iMGs at any point throughout the session. Our methodology for collecting video and iMG data is shown in Figure 1 and Table 1. The iMGs recorded time-stamped HAEs, which were sent via Bluetooth to a central device [1,6,23,29]. Video footage was collected from multiple angles at a resolution of 1080p and a frame rate of 30 fps during each on-field activity. HAEs were time-synchronized with match recordings via iMG timestamps and an on-field timer to facilitate visual verification and qualitative analysis. For each true positive HAE observed on film, the header type, ball delivery method and field location were classified. The raw agreement was 100.0% for the identification of headers. A Cohen's kappa coefficient was performed to assess the inter-rater reliability for contextual characteristics. For the header analysis, the raw agreement was 93.5%, and Cohen's kappa coefficient was 0.81 (95% CI 0.78–0.84) [30]. A Cohen's Kappa value greater than 0.8 is indicative of almost perfect agreement [31].

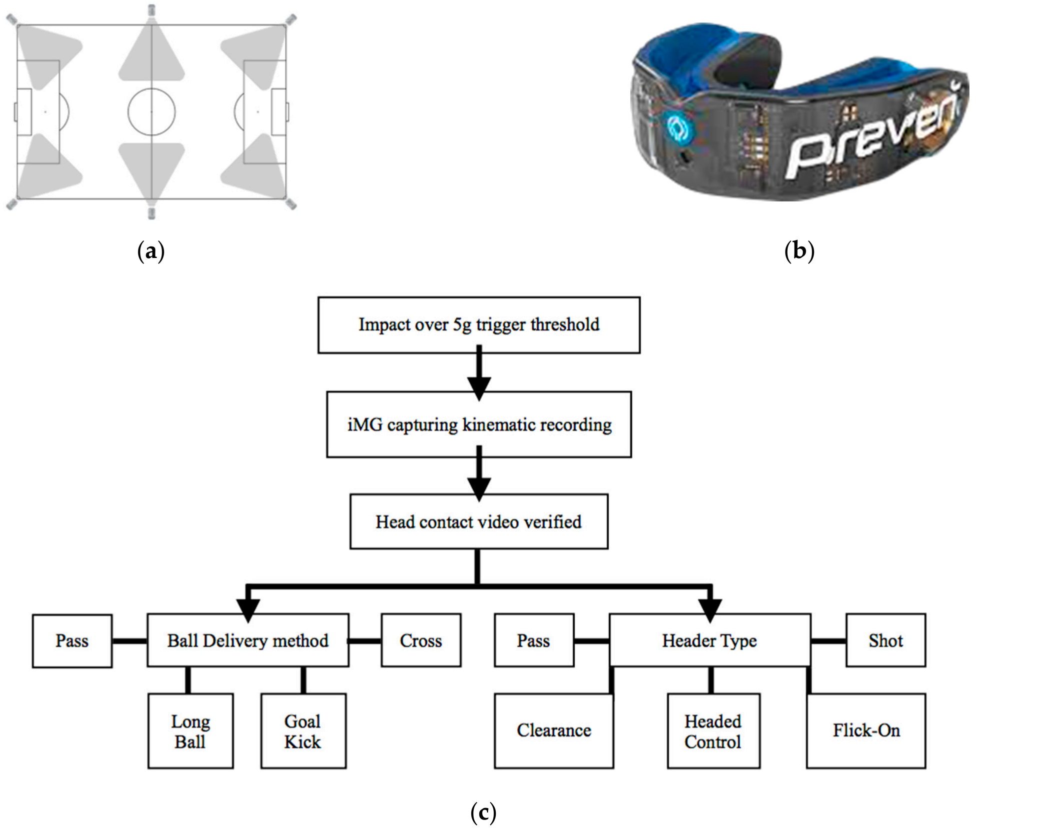

Figure 1. (**a**) The placement of digital cameras to record multi-angle, time-synchronized footage of header impacts, in combination with the (**b**) instrumented mouthguard utilized for the study. Section (**c**) summarizes the methodology of video analysis utilized to categorize each HAE into a contact scenario.

Table 1. Variables used to categorize header impacts through video incident analysis.

Pre-Head Contact	**Head Contact**
Ball Delivery Method • Cross (incl. Corner, Delivery into Box) • Goal Kick • Long Ball (incl. Clearance, High Ball) • Pass (incl. Chip, Headed Pass, Throw in)	*Header Type* • Clearance • Flick-On • Interception • Pass • Shot • Headed Control

Every iMG possessed an infrared proximity sensor to assess coupling to the upper dentition, as well as an accelerometer and gyroscope, both sampling at 3200 Hz, with measurement ranges of ±200 g and ±35 rad/s, respectively. The iMGs were configured to capture 10 ms of pre-trigger data and 40 ms of post-trigger data when the accelerometer detected over 5 g linear acceleration on a single axis of the iMG. A recording threshold of 5 g linear acceleration at the head center of gravity was selected, given that the previous threshold of 10g lacked sensitivity in capturing mild headers [1,32]. Previous studies have established the validity of the Prevent Biometric custom-fit iMG [25,33]. Liu et al. [33] found the Prevent Biometric custom-fit iMG to perform best in laboratory dummy headform testing with lower mean relative errors of 4.9%, 4.6%, and 2.5% for peak angular acceleration, angular velocity, and linear acceleration, respectively. Within lab and field-based testing, the Prevent Biometric custom-fit iMG performed highest with a concordance correlation coefficient value of 0.97 and a positive predictive value of 96% [34]. The Prevent Biometric custom-fit iMG has shown the highest performance in false-negative testing in rugby, in addition to receiving high ratings for comfort and functionality [35].

Data Analysis

Peak linear acceleration (PLA) and peak angular acceleration (PAA) were calculated from kinematic recordings by applying a rigid body transformation to the head's center of gravity. Dependent (continuous) variables included PLA and PAA. Fixed effects included the categorical variables of header type and ball delivery method. Data were visually inspected for normality using histograms and Q-Q plots. No data followed a normal distribution, and so the peak kinematics distributions (PLA and PAA) were expressed as medians and interquartile ranges (lower [25%] to upper [75%] quartiles). To minimize the error from non-uniform data, dependent variables were transformed prior to analysis (Log-transform for PLA and Square Root Transform for PAA). Linear mixed-effects models (IBM SPSS version 28) were used to evaluate nested data in clusters of individual players [29]. PLA and PAA were compared between the ball delivery method (model 1) and header type (model 2). To account for variability, the player subject factor was included as a random intercept for both models. A Bonferroni correction was applied to the p-values of the fixed effects to account for multiple comparisons. Significance was determined by comparing the p-values with an alpha level of $p < 0.05$.

3. Results

In total, 133 video-verified headers were recorded. For all headers, the median and interquartile range (IQR) for PLA was 13.5 g (IQR: 9.9–17.5 g) and PAA was 1094 rad/s^2 (IQR: 675–1595 rad/s^2). Approximately a quarter (25.6%) of headers were below 10 g, 59.4% were below 15 g, and 87.2% were below 20 g.

When categorized by header type, 37.6% (n = 50) were found to be pass attempts, 22.6% (n = 30) were flick-on attempts, 18.0% (n = 24) were clearance attempts, 14.3% (n = 19) were interceptions, 3.8% (n = 5) shot attempts, and 3.8% (n = 5) were headed controls. By the preceding ball delivery method, 45.1% (n = 60) were passes, 31.6% (n = 42) were long balls, 13.5% (n = 18) were goal kicks, and 9.8% (n = 13) were cross deliveries.

For the header type, there were no significant differences in kinematics, with shot attempts having the highest median PLA and PAA (Figure 2). For the ball delivery method, goal kicks had a significantly greater PAA than long balls and pass attempts (Figure 3).

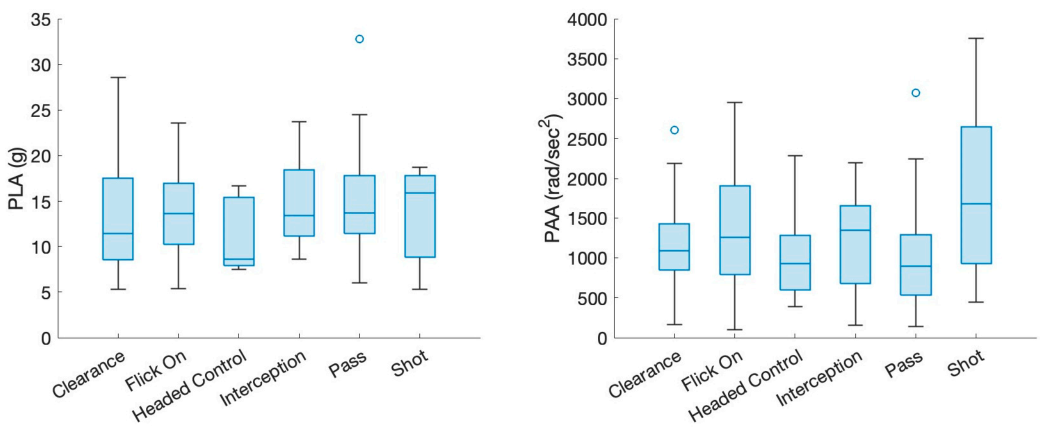

Figure 2. Heading kinematics based on the header types clearance (n = 24), flick on (n = 30), headed control (n = 5), interception (n = 19), pass (n = 50) and shot (n = 5). Tabulated results are available in Appendix A.

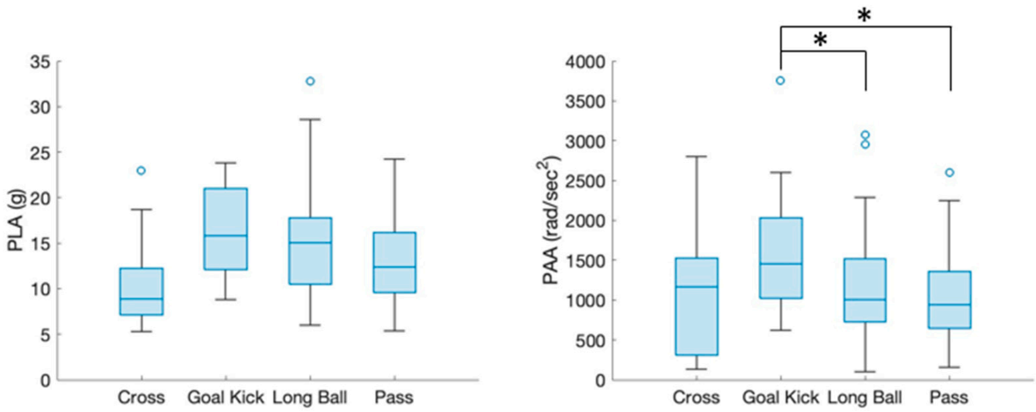

Figure 3. Heading kinematics based on the ball delivery methods cross (n = 13), goal kick (n = 18), long ball (n = 42) and pass (n = 60). Asterisks (*) indicate statistical significance between goal kicks and both long balls (p = 0.024) and pass attempts (p = 0.011). Tabulated results are available in Appendix A.

4. Discussion

Heading the ball is a fundamental aspect of soccer but exposes players to repeated sub-concussive impacts. Given the growing concerns surrounding the long-term sequelae attributed to heading, it is crucial to understand the biomechanics of header impacts and how they vary across different in-game contexts. To achieve this, we used custom-fit iMGs in combination with qualitative video analysis to identify on-field heading scenarios associated with higher HAE magnitudes. Our findings provide initial insight for the development of player protection strategies based on the principle that reducing the magnitudes of HAEs may potentially mitigate the adverse effects of heading on brain health.

The current study revealed no significant variations in head kinematics among differing header types, aligning with the results of previous research in female collegiate players [6]. However, it is important to note that our study only examined HAEs during games, yet previous research has shown that HAEs during practice can be just as significant [1]. This highlights the need for monitoring HAE during both practices and games, as reducing heading frequency during practices may be a more effective way to lower overall HAE exposure and severity. Currently, efforts to reduce HAEs have mainly focused on goal kicks [36]; however, prior research found them to occur infrequently and thus not significantly contribute to the cumulative heading load experienced by athletes [37]. Instead, Harris et al. [37] noted that aerial passes made up the largest portion (41%) of headers executed by players, a trend our study also confirmed at 45.1%. By limiting the number of practices in which athletes participate in aerial passes, we may be able to reduce head acceleration exposures. This notion is supported by a study of youth football athletes that demonstrated a 37% reduction in the number of head contacts when limiting contact in practices to one-third of the total practice time [38]. However, a direct measure of HAE exposures within heading-restricted training sessions has yet to be conducted and represents an important future consideration.

Another approach to decrease HAEs in soccer is to identify and alter the in-game contexts that are associated with the most severe headers. Previous research utilizing multibody models has established that the force experienced during header impacts is primarily derived from the velocity of the ball rather than its mechanical properties [39]. The current research supports this finding, as goal kicks, which tend to result in the highest heading ball speeds [40], were found to have significantly greater resultant PAA than long balls or pass attempts. Similarly, comparable iMG studies in women's collegiate soccer have revealed significant differences in mean peak rotational acceleration between headers from goal kicks and those during live-play scenarios [6]. Given these findings, modifications to goal kicks present a unique opportunity to decrease the peak speeds at which players head the ball, thereby reducing the cumulative exposure to head acceleration. Player protection strategies such as replacing goal-kicks with roll-outs or head height rules at certain levels of play could mitigate the most severe headers [40,41]. Additionally, strategies may include changes in regulations, such as the Football Association's 2019 introduction of allowing a teammate to be within the penalty area when the goal kick takes place [42]. This change was initially intended to limit in-match pauses, but researchers subsequently observed a decrease in the frequency of long goal kicks as a result [43]. Shibukawa and Hoshikawa [43] found that, by comparing the 2018 and 2020 seasons of the Japanese premiership, goalkeepers were more likely to perform short pass-like kicks instead of long clearing strikes in order to retain possession. The shift in strategy reduced player engagement in aerial heading challenges, leading to a decrease in the exposure to HAEs [43]. However, while these modifications have been beneficial in elite competition, their potential benefits may not be fully realized at lower levels of play. This is partly due to amateur players' limited ability to initiate an attack from the defensive end, resulting in a greater reliance on long goal kicks as a means to effectively progress the ball up the field [40,44]. Instead, league officials have begun banning heading within youth matches [45], but officials fear that such absolute measures may hinder the proper development of heading technique [6]. Thus, efforts should focus on ensuring appropriate head contact with the ball, which has been shown to significantly reduce the shear forces encountered by the brain [22]. Studies of youth players found that headers performed using the top of the head resulted in larger rotational velocities [1]. To mitigate this, training programs should instruct players to contact the ball using the front of their head, reducing the magnitude of linear head acceleration experienced [1]. However, more research is needed to understand the effects of the heading technique on head kinematics in adult players.

Most studies on HAEs in soccer have focused on collegiate women's soccer [1,6,7,46] and female youth players [47,48], while male players across all ages have been underrepresented. Additionally, few studies have utilized iMGs in conjunction with video review to analyze the context of recorded HAEs [46]. To obtain comparable data between studies and to accurately evaluate the risk of concussion/long-term injury, it is crucial to standardize measurement methodology. For example, Lamond et al. [7] found significant differences in linear head acceleration during different types of play but did not investigate rotational head acceleration, which appears to be a primary contributor to brain injury [46]. The brain's mechanical profile, with a high bulk modulus and low shear modulus, makes it resilient to changes in volume but vulnerable to changes in shape during impact [22]. As a result, the brain primarily deforms in shear when impacted, likely rendering it more susceptible to rotational loading [22]. Until more research is done on the validity of brain injury criteria, it is important to consider both linear and rotational kinematics when assessing the risk of concussion injury and head acceleration exposure. An earlier study [36] that measured both PLA and PAA reported average peak linear (28.2 g) and angular (7.1 krad/s^2) accelerations greater than the 95th percentile values found in the current study (23.9 g and 2.3 krad/s^2, respectively). These higher kinematic values reported by Caccese et al. [36] may be partly due to measurement errors caused by relative motion between the skin and skull when using headband-based sensors [22]. Alternatively, iMGs provide a more accurate and reliable measurement of skull acceleration by directly coupling with the upper dentition and, thus, are the favored choice for evaluating HAEs [23]. Compared to previous female iMG kinematics [1,6], our study found that male collegiate soccer players experienced higher median header magnitudes. However, further studies are needed to understand any potential sex-based discrepancies.

Of the 133 HAEs analyzed in this study, 25.6% (33) occurred at an PLA of less than 10 g at the head's center of gravity. The threshold used to measure minimum acceleration can significantly affect the data obtained [22]. Higher thresholds may overlook lower-magnitude HAEs and underestimate cumulative HAE exposure over a player's career [49]. Therefore, caution must be exercised when comparing studies, as variations in threshold levels and sensor technologies can result in varying measurement errors and HAE incidence. The clinical significance of these lower-magnitude headers in soccer players is not yet fully understood [23]; however, it is thought that chronic exposure to sub-concussive impacts may increase the risk of neurodegenerative diseases [6]. One study found that professional football players were 3.5 times more likely to die from neurodegenerative diseases, including a 5.1 times higher risk of dying from Alzheimer's disease and a 4.3 times higher risk of dying from motor neuron disease [50]. However, other studies have not found a clear correlation between heading exposure and adverse outcomes [19,51]. It is important to note that prior studies have often quantified heading exposure through self-reported questionnaires or controlled laboratory environments, which may not accurately reflect the range and magnitude of headers experienced in competitive game contexts [6]. This study did not evaluate the potential relationship between biomechanical measures and neurocognitive clinical outcomes, but it could be the focus of future studies. By eliciting the effects of repeated sub-concussive impacts on neurocognition, we may begin to understand the risk of concussion beyond peak kinematic values alone.

This study provides valuable insights into the correlation between header kinematics and the contexts in which they occur; however, it is important to note certain limitations. This study only included male soccer players participating in a university intra-mural football league, so the characterizations of heading scenarios provided herein may not be generalizable to other cohorts. Additionally, the study only examined competitive matches, and future research should include HAEs during training sessions to obtain a more comprehensive understanding of HAE kinematics. The methods used to measure heading-related exposure (PLA and PAA) have certain shortcomings, specifically in terms of not considering the direction and time duration of head kinematic signals, which could be crucial in determining the degree of brain tissue deformation from a HAE [22,52,53]. Although custom-fit mouthguards were used, further research is needed to investigate the influence of mouthguard fit on head kinematic measurement error [29]. The sample size of 10 players from a single college during a season of play is relatively small, and therefore the purpose of this study was not to report incidence/exposure metrics. To develop effective player protection recommendations, future studies should capture kinematic data from both matches and training sessions across a large cohort of male and female athletes and different levels of play. Our analysis revealed a lack of adherence to mouthguard use, with an average of only 2.8 players per match wearing them, with many not using them for the entire match. Previous research has shown that soccer players are among the least likely to use mouthguards despite their effectiveness in preventing orofacial injuries [54]. A study by Collins et al. [55] found that players commonly cited discomfort, lack of coaching instruction, and difficulty breathing as reasons for non-compliance. Despite the development of custom-fitted mouthguards having largely eliminated these issues, usage still remains low [56]. To address this, efforts should focus on educational initiatives. Previous research has shown that 78.3% of athletes were unaware of the benefits of mouthguard use, and 97.1% of these athletes had never used a mouthguard [57]. Coaches and athletic trainers can play a crucial role in increasing mouthguard use by educating athletes about the importance of brain injury research, holding them accountable for their behavior, and reducing stigma in making healthy choices [54]. Over 50% of participants in previous studies have indicated that they would wear mouthguards if their coach told them to, and over 30% have indicated the same about athletic trainers [54]. Therefore, coaches and athletic trainers can be essential in promoting mouthguard use, but educational initiatives are needed to increase awareness and promote use among soccer players.

5. Conclusions

The current study analyzed 133 film-verified header scenarios with iMG kinematic measures during university intra-mural football league matches to inform future heading mitigation strategies. For header type, there were no significant differences in kinematics, with shot attempts having the highest median PLA and PAA. For the ball delivery method, goal kicks had significantly greater PAA than long balls and pass attempts. The study highlights the utility of combining qualitative video analysis with real-time head kinematic data to better understand the mechanisms and severity of header impacts. The findings indicate that high-speed ball delivery methods, such as goal kicks, result in higher head kinematics and provide insight into potential future mitigation strategies (e.g., replace goal kicks with rollouts or head height rules at certain levels of play). The pilot study provides valuable insights for developing effective player protection strategies, with a primary focus on reducing HAEs to potentially limit the negative effects associated with heading the ball.

Author Contributions: Conceptualization, G.T.; methodology, G.T.; software, all authors.; validation, all authors; formal analysis, all authors; investigation, O.W.S.-H. and D.S.-R.; resources, all authors; data curation, all authors; writing—original draft preparation, D.S.-R. and G.T.; writing—review and editing, all authors.; visualization, D.S.-R., D.A. and G.T.; supervision, G.T.; project administration, all authors. All authors have read and agreed to the published version of the manuscript.

Funding: This research did not receive any specific grant from funding agencies in the public, commercial, or not-for-profit sectors. The iMGs were provided in kind by Prevent Biometrics for research use.

Institutional Review Board Statement: The study was conducted in accordance with the Declaration of Helsinki and approved by the Ethical Review Committee at the University of Leeds (#BIOSCI 19-026).

Informed Consent Statement: Informed consent was obtained from all subjects involved in the study.

Data Availability Statement: Anonymized data available subject to reasonable request.

Acknowledgments: We would like to acknowledge Prevent Biometrics for supplying the instrumented mouthguards and providing ongoing technical assistance throughout the project. Additionally, we express our appreciation to the players and staff of the Leeds University Inter-mural Football League for making this study possible.

Conflicts of Interest: The authors declare no conflict of interest.

Appendix A. Header Kinematics by Header Type and Preceding Ball Delivery Method

	N = 133	PLA (g)		PAA [krad/s^2]	
		Median	**[Q1,Q3]**	**Median**	**[Q1,Q3]**
		Header Type			
Clearance	n = 24	11.4	[8.4,17.6]	1091.5	[826.5,1459.5]
Flick-on	n = 30	13.6	[10.0,17.1]	1255	[775.8,1925.3]
Headed Control	n = 5	8.6	[7.8,15.9]	930	[529.0,1616.5]
Interception	n = 19	13.4	[11.0,18.5]	1349	[675.0,1663.0]
Pass	n = 50	13.7	[11.2,17.9]	893.5	[532.3,1342.8]
Shot	n = 5	15.9	[7.7,18.1]	1686	[765.0,3013.5]
		Ball Delivery Method			
Cross	n = 13	8.9	[7,12.5]	1165	[275.0,1554.5]
Goal Kick	n = 18	15.85	[12.08,21]	1451.5	[1018.5,2071.8]
Long Ball	n = 42	15.05	[10.5,17.9]	1002.5	[718.3,1535.0]
Pass	n = 60	12.35	[9.6,16.23]	945.5	[636.0,1368.0]

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