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ORIGINALIA

Factors Influencing Wearable-Derived Head Impact Kinematics in Soccer Heading

Einflussfaktoren auf die mittels tragbarer Sensortechnik erfasste Kopfbeschleunigung bei Kopfbällen im Fußball

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Summary

› **Problem Statement:** Soccer players expose themselves to repetitive head impacts (RHI) by purposefully heading the ball – an act that has been suggested to adversely affect brain structure and function and potentially contribute to the long-term development of neurodegenerative disorders. A deeper understanding of the head's kinematic response to these RHI is crucial to assess the actual risk resulting from routine soccer heading. To that aim, we investigated the influence of a comprehensive set of heading-related factors on the resulting linear and rotational acceleration of the head, as obtained by wearable sensors in a field study.

› **Methods:** Across 26 matches, 19 semi-professional female soccer players (23.0±3.7 years) were equipped with wearable head impact sensors that registered peak linear acceleration (PLA) and peak rotational acceleration (PRA) of on-field head impact events. Actual headers were confirmed and further allocated to the following categories using video analyses: Scenario, Distance, Player Movement, Ball Reflection, Impact Location, Duel, Jump. Linear mixed models were used to assess the relationships between these factors and PLA as well as PRA.

› **Results:** Average PLA and PRA of the head due to heading was 29.6 (±18.1) g and 6195.6 (±4448.1) rad/s^2, respectively. Analyses revealed a statistically significant influence of three factors on both PLA (R2=0.34) and PRA (R2=0.37). Next to subject-related factors (p<0.001; proportional variance: 12.6% [PLA] and 19.0% [PRA]), especially longer in-air distances of the ball prior to heading (p<0.001; proportional variance: 24.6% [PLA] and 19.2% [PRA]) as well as a greater extent of ball reflection due to a header (p<0.001; proportional variance: 9.2% [PLA] and 6.9% [PRA]) were significantly associated with increases in head impact kinematics.

› **Conclusion:** Our findings demonstrate that the ball's travelling distance and the extent of ball reflection due to a header directly affect the head's kinematic response to purposeful headers in female players. Along with these factors, future studies should focus on the direct assessment of inter-individual differences in heading technique and anthropometric variables to increase the current understanding of the potential risk resulting from RHI due to soccer heading.

KEY WORDS:
Repetitive Head Impacts, Head Impact Kinematics, Wearable Sensors, Concussion, On-Field

Introduction

Similar to athletes participating in other types of contact or collision sports, soccer players face an increased risk for sustaining impacts to the head as a result of tackles, collisions, or falls. However, soccer is also unique in that players deliberately expose themselves to repetitive head impacts (RHI) by intentionally heading the ball. While these purposeful headers usually do not present with overt signs and symptoms of concussions or (mild) traumatic brain injuries (mTBI), the frequency and repetitiveness of these subconcussive head impacts have put the act of heading under scrutiny (2, 23). Within this context, reports of cognitive impairment (35) and an increased risk for the development of neurodegenerative disorders (26) in (former) professional soccer players have led to concerns that the subtle effects of numerous headers over a prolonged period of soccer participation might accumulate and foster the development of long-term neurological deficits (14).

Next to the assessment of soccer players' typical number of headers across different age groups and the longitudinal examination of header-related effects on brain structure and function, a deeper understanding of the head's kinematic response to purposeful headers (i.e., head acceleration) can be seen as a crucial factor for the valid assessment of the risk resulting from these RHI (6, 20) – especially when considering the proposed association between head impact magnitude and acute head injury (31) as well as cumulative brain damage (11). While the earliest approaches dealing with the biomechanics of head impacts resulting from purposeful heading have been conducted in controlled laboratory environments (4, 28), in recent years, a modest number of studies have exploited the potential of wearable sensor technologies to also collect header-related head acceleration data during on-field matches. With average peak linear and rotational acceleration values ranging from 11.7 g to 28.2g and 723.2 rad/s^2 to ›

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Table 1
Sample characteristics.

	MEAN (±SD)	RANGE
Age [a]	23.0 (±3.7)	18-31
Height [cm]	168.2 (±4.1)	163.0-177.0
Mass [kg]	62.0 (±5.3)	49.0-72.0
BMI [kg/m²]	21.9 (±1.9)	18.2-25.8
Soccer Experience [a]	17.0 (±4.4)	10.0-27.0
Training / Week [h]	4.8 (±1.5)	2.0-8.0

7100.0 rad/s^2, respectively (7, 12, 15), these studies reported a considerable variability in impact magnitudes of purposeful headers. In particular, previous research has shown header biomechanics to vary according to different in-game conditions, such as the scenario preceding the header, the ball's impact location on the head, and a player's postural state (i.e., standing or jumping). With respect to in-game scenarios, a common finding was that headers following goal-kicks and/or free kicks resulted in significantly greater linear and rotational head accelerations than headers that were performed from throw-ins or previous headers (7, 12, 27). A greater distance travelled by the ball prior to the header event is associated with higher ball velocities, which consequently cause the observed increases in impact kinematics. Based on this, Caccese et al. (7) suggested that limiting headers from goal-kicks and punts might reduce soccer players' exposure to cumulative head accelerations and, in this sense, protect athletes from the potentially adverse effects of repetitive headers. Concerning impact location, striking the ball with the forehead has been commonly referred to as 'correct' or proper heading technique (1, 20) owning the potential to decrease impact magnitudes. In line with this, Harriss et al. (16) found that headers performed with the top of the head came along with significantly higher peak rotational velocities than forehead headers. Their results were confirmed by Kenny et al. (17), who reported significantly lower impact magnitudes (both linear and rotational acceleration) for frontal headers as compared to impacts to the top of the head. In a recent study, Filben et al. (13) could, indeed, demonstrate the potential of a proficient heading technique for reducing impact magnitudes of purposeful headers. However, as the calculation of their technique score comprised additional factors, such as back extension or body weight transfer into the anterior direction, an exclusive focus on the ball's impact location for determining heading technique might be misleading – especially when considering that striking the ball with the side or the back of the head can be termed appropriate to redirect the ball to the side or reflect it in its original direction, respectively. This notion is reinforced by the results of an earlier study from Hanlon & Bir (15), who found the lowest head accelerations to occur from headers performed with the back of the head. Ultimately, Kenny et al. (17) systematically examined players' postural state as a potential factor to affect heading kinematics and reported that jumping headers were associated with significantly greater head accelerations than headers performed in a standing position.

While these studies demonstrate the importance of considering different in-game conditions and heading characteristics when assessing header-related impact biomechanics, only Kenny et al. (17) investigated the effects of the three aforementioned factors (in-game scenario, impact location, postural state) within a single study, whereas other approaches (7, 15) commonly focused on the investigation of single factors. Given considerable differences in sample characteristics (e.g., youth vs. college athletes) and sensor types with varying properties (e.g., mouthpiece vs. headband vs. skin-patch sensors), a comparative interpretation of individual findings proves difficult. Moreover, to the best of our knowledge, the effects of other header-related factors on the resulting linear and rotational head acceleration – such as player movement towards the ball, opponent involvement (heading duel vs. unchallenged header), and ball reflection due to heading – have not been investigated systematically. To address this gap, expand existing knowledge, and create novel insights about the head's kinematic response to varying conditions of routine soccer heading, the aim of the present study was to examine the influence of a comprehensive set of factors on wearable-derived head impact kinematics resulting from purposeful headers. To achieve this, we deployed wearable head impact sensors to a sample of semi-professional female soccer players in order record header-related impact kinematics during competitive matches. Video-recordings of these matches were then used to verify sensor data and contextualize identified header events. We hypothesized that especially longer in-air distances of the ball prior to heading would lead to higher PLA / PRA of the head. We further expected that headers performed with the forehead as well as unchallenged headers to result in lower impacts magnitudes.

Materials and Methods

Participants

A total of 23 female soccer players were recruited from a semi-professional female soccer team (German 3rd division) and provided written informed consent to participate in the study, which was approved by the ethical committee of the School of Medicine and Health of the Technical University of Munich. Of this original sample, 19 athletes (mean age: 23.0±3.7 years, mean height: 168.2±4.1cm, mean body mass: 62.0±5.3kg) were included in final data analyses as they performed a minimum of one intentional header throughout the observational period. Sample characteristics are presented in table 1.

Instrumentation

Across 26 competitive matches, soccer players were equipped with individually assigned inertial sensors (xPatch, X2 Biosystems, Seattle, USA) to register head impact kinematics resulting from purposeful headers. The xPatch devices contain a triaxial accelerometer (1000 Hz) and gyroscope (800 Hz) to register linear acceleration and rotational velocity of the head and have been used in a variety of studies dealing with head impacts in unhelmeted sports (9, 25, 29). Although the selected devices have been suggested to not always accurately capture both linear and rotational head accelerations (10, 37), we nevertheless opted for using the xPatch sensors as they have been shown to be more accurate than other wearable head impact sensors for use in unhelmeted sports at the time of data collection (10). Moreover, the here-adopted within-subject design still allows for an informative comparison between head impact kinematics resulting from different in-game conditions. Before all matches, a previously trained member of the team's staff affixed the sensors to the skin covering the players' right mastoid process using a double-sided adhesive cloth tape. As soon as an impact exceeded a pre-selected acceleration threshold of 8 g, three-dimensional linear acceleration and rotational velocity data were recorded for 100 ms (10 ms pre-trigger, 90 ms post-trigger) and 80 ms (post-trigger only due to the lower

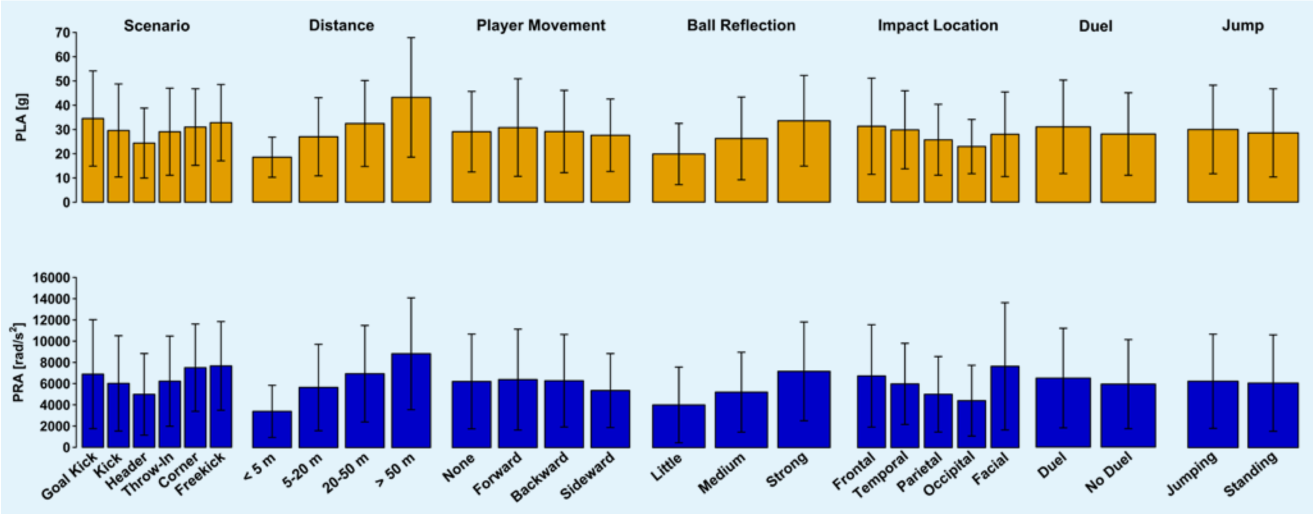

Figure 1

Graphical representation of average PLA (orange) and PRA (blue) resulting from purposeful headers across the different factors and their associated levels. No headers occurred following goal-directed shots (Scenario) and, therefore, no values are depicted.

gyroscope sample rate), respectively and stored internally. Since it was previously demonstrated that soccer headers result in impact magnitudes well below the commonly applied 10 g threshold (19), we opted for this reduced trigger threshold of 8 g to capture as many header events as possible. After each match, sensor-recordings were downloaded to a PC by the sensor manufacturer's proprietary software (Impact Monitoring System, X2 Biosystems) and stored for further analysis.

Procedures

Post-processing of sensor data was performed using the X2 monitoring system. Rotational acceleration was calculated from the gyroscope data using five-point differentiation (36). The three-dimensional linear and rotational acceleration data of each sensor-recorded event were transformed to the head's estimated center of gravity (CG), to then compute both the resultant peak linear acceleration (PLA) and the resultant peak rotational acceleration (PRA) at the head's CG (33, 36). To be able to independently verify sensor-recorded impact data and further obtain contextual information of the performed headers, video footage of the 26 matches was recorded by means of two high-definition video cameras (Sony HDR-CX653, Sony Corp., Tokyo, Japan) recording 50 fps at 1080p resolution. Before the matches, each camera was mounted on a tripod, which were located at opposing sides of the pitch near the midpoint with each of them capturing one half of the pitch (19). In the first step of a two-fold verification procedure, a trained researcher reviewed the match videos in order to identify actual header events and, along with their associated time stamps, assign them to the corresponding players. For a comprehensive categorization of headers, video-observed events were further coded according to pre-defined levels of the following factors: Scenario, Distance, Player Movement, Ball Reflection, Impact Location, Duel, and Jump (table 2). For both the identification of headers from video footage, and the subsequent categorization, a randomly selected subset of five matches was reviewed and analyzed by a second independent reviewer. Interrater reliability was assessed in terms of absolute agreement by computing the intraclass correlation coefficient (ICC, identification of headers from video footage time stamps) and Cohen's kappa (categorization of headers). In the second step of cross-verification, time stamps of video-identified headers and sensor-recorded impact events were precisely matched to each other. To achieve this, we used a time window of±2 seconds – i.e., any sensor recording occurring within 2 seconds of a video-observed header was assigned to the respective event (22).

Statistical Analysis

Statistical analyses were performed using R (R version 4.1.2, Rstudio version 2023.06.1, Rstudio PBC, Boston, USA). The α-level was set to 0.05 throughout. The absolute numbers and the relative frequency of headers across the different factor levels are displayed as absolute values and percentages, respectively. Unless otherwise stated, all other descriptives are presented as means (±SD). To assess the relationships between the defined factors and the dependent variables PLA and PRA, two separate linear mixed-effects models were computed using the lme4 package (3). In an initial step, all pre-defined predictor variables (Scenario, Distance, Player Movement, Ball Reflection, Impact Location, Duel, Jump), Subject, Subject Mass, and all possible two-way interaction terms were included in the model. While the in-game variables as well as Subject were considered random factors, Subject Mass was modelled as a fixed factor. We then employed a stepwise backward selection procedure to remove the predictor variable with the highest p-value at each step, until only statistically significant predictors ($p<0.05$) remained in the model. The critical variance inflation factor (VIF) was set to 5.0.

Results

Analysis of interrater reliability revealed an excellent agreement (21) for the identification of soccer headers from video data (ICC=0.96, 95% CI [0.94-0.97]) as well as a substantial to almost perfect agreement (24) between the two raters for the categorization of header events into the defined categories ($0.76<\kappa<0.93$). Video analysis of the 26 matches revealed a total of 1016 purposeful headers performed by the instrumented players. For 904 (i.e., 89.0%) of these video-identified headers, a corresponding sensor event could be unequivocally determined. Out of these, 899 (99.4%) headers were fully categorized and, thus, included in the analysis. In all five cases, incomplete categorization was due to the fact that the scenario prece-

Table 2

Definitions of factors and factor levels for the contextual categorization of video-identified headers.

FACTOR	DESCRIPTION	LEVELS	DEFINITION
Scenario	In-game scenario preceding a header	Goal-Kick	Header following a goal-kick
		Kick	Header following a kick during open play
		Shot	Header following an intentional shot on goal
		Header	Header following another header
		Throw-In	Header following a throw-in
		Corner	Header following a corner-kick
		Freekick	Header following a free kick
Distance	Distance travelled by the ball prior to the header	< 5 m	Distance < 5 meters
		5-20 m	Distance between 5 and 20 meters
		20-50 m	Distance between 20 and 50 meters
		> 50 m	Distance > 50 meters
Player Movement	Movement of the player prior to heading	None	No player movement prior to heading
		Forward	Forward movement prior to heading
		Backward	Backward movement prior to heading
		Sideward	Sideward movement prior to heading
Ball Reflection	Extent of the ball's change of original direction due to the header	Little	Ball "flicked" on in original direction
		Medium	Ball re-directed approx. 90° from original direction
		Strong	Ball headed back towards its original direction
Impact Location	Impact location on the player's head	Frontal	Impact on the forehead
		Temporal	Impact on the side of the head
		Parietal	Impact on the top of the head
		Occipital	Impact on the back of the head
		Facial	Impact on the face
Duel	Header duel vs. unchallenged header	Duel	Opponent within 1 meter of heading player
		No Duel	No opponent within 1 meter of heading player
Jump	Jumping vs. standing header	Jumping	Jumping header
		Standing	Standing header

ding the header could not be unequivocally identified as, for some matches, small areas of the pitch could not be covered on video. For all headers, average PLA and PRA was 29.6 (±18.1) g and 6195.6 (±4448.1) rad/s^2, respectively. There was a strong positive relationship between PLA and PRA (r=0.79, p<0.001), as revealed by a Pearson's correlation analysis. Table 3 displays the absolute number and the relative frequency of headers across the different factors and their associated levels as well as the average values of PLA and PRA. A graphical representation of the average impact kinematics across the different factors and their associated levels is provided in figure 1.

For the identification of factors influencing PLA from purposeful heading, the employed backward selection procedure resulted in a statistically significant model explaining 33.5% of variance (p<0.001). The factors Subject (p<0.001), Distance (p<0.001), and Ball Reflection (p<0.001) turned out to be statistically significant predictors of PLA. More specifically, increases in the distance travelled by the ball prior to heading led to greater PLA values. Similarly, a greater extent of ball reflection due to heading resulted in higher PLA of the head. The factor Distance was the highest contributing factor (proportional variance: 24.6%), followed by Subject (proportional variance: 12.6%) and Ball Reflection (proportional variance: 9.2%). No statistically significant interactions were observed between the included predictor variables.

Concerning the factors' influence on PRA due to heading, our analysis resulted in a similar model explaining 37.0% of variance (p<0.001), which comprised the factors Subject (p<0.001), Distance (p<0.001), and Ball Reflection (p<0.001) as statistically significant predictors of PRA. Again, a longer travelling distance of the ball prior to heading as well as a greater extent of ball reflection due to heading were associated with larger PRA of the head. With a proportional variance of 19.2%, Distance was the highest contributing factor, followed by Subject (proportional variance: 19.0%) and Ball Reflection (proportional variance: 6.9%). As for PLA, no statistically significant interactions were observed between the included predictor variables.

Discussion

To validly assess the potential risk of routine soccer heading, a sophisticated understanding of the head's kinematic response to these RHI in actual on-field settings is crucial. In this study, we investigated the influence of a comprehensive set of heading-related factors on the resultant peak linear acceleration (PLA) and peak rotational acceleration (PRA) of the head, as obtained by wearable sensors. Video footage of 26 competitive matches of a semi-professional female soccer team was reviewed to identify purposeful header events, which were further coded according to pre-defined categories, and subsequently matched with their corresponding sensor recordings. We found that, next to subject-related factors, especially longer in-air distances of the ball prior to heading as well as a stronger ball reflection due to the header were significantly associated with increases in both PLA and PRA. These findings add to the limited body of knowledge regarding differences in head impact magnitudes from in-game soccer heading.

Average PLA and PRA of the 899 headers that were included in our analysis was 29.6 (±18.1) g and 6195.6 (±4448.1) rad/s^2, respectively. These impact magnitudes are slightly higher than the ones reported in two studies (30, 32), which used the same skin patch sensor model to examine header-related impact kinematics in collegiate female players. More specifically, Press & Rowson (30) observed an average PLA of 25 g and an average PRA of 5709 rad/s^2. Similarly, Saunders et al. (32) reported mean PLA and PRA values of 26.7g and 5758.8 rad/s^2 in their subsample of female players, respectively. While these differences appear to be marginal at first glance, it has to be noted that the two mentioned approaches employed a 10 g linear acceleration trigger, whereas we opted for a reduced trigger threshold of 8 g. Given that our data, consequently, contain a greater amount of low intensity headers between 8 g and 10 g (6.3%) as compared to previous studies (30, 32), these differences in head acceleration from purposeful heading would have been more pronounced if we would have selected a 10 g trigger. A reason for the observed differences in PLA and PRA may be seen in the older age and/or the higher level of play of our semi-professional female athletes as compared to the collegiate players in the studies of Press & Rowson (30) and Saunders et al. (32). In general, previous research on soccer-related head impacts has observed a trend towards higher-magnitude impacts as players progress into higher levels of play (12, 27), which has been attributed to general increases in strength and the capability of kicking the ball further distances at higher velocities (12).

In line with our hypothesis and basic mechanics, the above-stated notion is underpinned by our results as we identified Distance as the highest contributing factor to significantly influence both PLA and PRA of the head following heading, with longer-distance kicks leading to greater head accelerations than scenarios associated with shorter travelling distances of the ball. Similarly, both Kenny et al. (17) and Miller et al. (27) reported "long kicks" to result in higher impact magnitudes (both PLA and PRA) as compared to "short kicks". Although we were not able to register ball velocities prior to heading, the observed increases in head impact magnitudes most likely result from the higher kinetic energy of the ball, which, in turn, results from higher ball velocities required to achieve longer kicking ranges. However, unlike previous studies (7, 12, 27), who reported significant differences in impact kinematics between different in-game scenarios (e.g., goal kick vs. throw-in), the factor Scenario did not turn out to be a significant predictor of either PLA or PRA. Therefore, the distance travelled by the ball prior to heading appears to be a more valid predictor of head impact kinematics as compared to the preceding in-game scenario.

While other variables that have been previously reported to be associated with differences in head impact kinematics during heading – such as head impact location (16, 17) or players' postural state (17) – did not significantly explain variations in PLA or PRA in the present study, we identified the factor Ball Reflection to significantly influence both PLA and PRA of the head when purposefully heading the ball. Within this context, a greater extent of ball reflection (i.e., larger angle of ball reflection, with 180° theoretically denoting perfect reflection of the ball back towards its original direction) was associated with increases in peak head impact kinematics as compared to headers during which the ball was re-directed in its original direction ("flicked on"). To the best of our knowledge, this parameter has not been previously evaluated with respect to its influence on header-related head impact kinematics in actual on-field settings. However, in an early experimental approach, Shewchenko et al. (34) reported the highest head impact magnitudes to result from headers with a pronounced redirection of the ball (e.g., towards the ground near the player). Similarly, in an experimental pilot study, we found that headers that were performed with a soccer ball pendulum resulted in larger impact angles and the greatest change in head velocity due to heading (18). This is logical, considering the ratio of ball energy being

Table 3

Absolute numbers and relative frequencies of headers along with the average PLA and PRA values across the different factors and their associated levels.

	N (%)	PLA (±SD) [G]	PRA (±SD) [RAD/S²]
ALL HEADERS	**899 (100.0)**	**29.6 (±18.1)**	**6195.6 (±4448.1)**
SCENARIO			
Goal-kick	112 (12.5)	34.5 (±19.6)	6890.0 (±5130.4)
Kick	359 (39.9)	29.9 (±19.2)	6034.1 (±4487.6)
Shot	0 (n.a.)	n.a. (n.a.)	n.a. (n.a.)
Header	150 (16.7)	24.4 (±14.4)	4989.1 (±3845.7)
Throw-in	171 (19.0)	29.1 (±18.0)	6241.2 (±4267.9)
Corner	47 (5.2)	31.0 (±15.8)	7501.9 (±4113.7)
Freekick	60 (6.7)	32.9 (±15.8)	7702.5 (±4202.5)
DISTANCE			
<5m	97 (10.8)	18.5 (±8.3)	3432.9 (±2458.9)
5-20m	392 (43.6)	26.9 (±16.1)	5659.8 (±4072.9)
20-50m	322 (35.8)	32.4 (±17.7)	6955.4 (±4543.4)
>50m	88 (9.8)	43.1 (±24.6)	8829.6 (±5261.5)
PLAYER MOVEMENT			
None	128 (14.2)	29.0 (±16.6)	6241.6 (±4469.9)
Forward	427 (47.5)	30.5 (±19.9)	6375.4 (±4728.1)
Backward	213 (23.7)	29.1 (±16.9)	6310.1 (±4349.2)
Sideward	131 (14.6)	27.5 (±14.9)	5366.4 (±3478.1)
BALL REFLECTION			
Little	134 (14.9)	19.8 (±12.6)	4013.4 (±3558.9)
Medium	234 (26.0)	26.2 (±17.1)	5214.4 (±3769.4)
Strong	531 (59.1)	33.5 (±18.5)	7175.7 (±4634.1)
IMPACT LOCATION			
Frontal	546 (60.7)	31.1 (±19.7)	6724.3 (±4800.5)
Temporal	137 (15.2)	29.7 (±16.1)	5994.3 (±3816.1)
Parietal	189 (21.0)	25.7 (±14.6)	5008.8 (±3556.0)
Occipital	24 (2.7)	22.9 (±11.2)	4416.5 (±3328.0)
Facial	3 (0.3)	27.9 (±17.4)	7647.4 (±5987.8)
DUEL			
Duel	427 (47.5)	31.0 (±19.1)	6484.9 (±4681.7)
No Duel	472 (52.5)	28.2 (±17.0)	5930.6 (±4209.1)
JUMP			
Jumping	702 (78.1)	29.8 (±18.1)	6228.2 (±4420.4)
Standing	197 (21.9)	28.5 (±18.2)	6071.6 (±4545.1)

dependent on a trigonometric function of the impact angle. Our results suggest that headers strongly redirecting long distance shots generate the highest head accelerations. A gameplay indication would be to recommend players to not fully reflect long distance shots back towards their original direction. However, players will most likely compromise the potential consequences for brain health if they consider such headers crucial for the outcome of a match. Introducing a rule forbidding such headers would not be feasible, since there would be too much uncertainty in close-to-threshold distance scenarios.

Ultimately, we found a significant contribution of the factor Subject on peak head impact magnitude (both PLA and PRA) due to heading. This might be reflective of inter-individual differences in heading technique, as recently suggested by Filben et al. (13). More specifically, the authors found that back extension and shoulder/hip alignment led to significant attenuations in peak head impact kinematics following headers in their sample of female youth soccer players (13). Similarly, players' anthropometric or kinetic characteristics – such as variations in head and neck size or neck strength (5) – probably contribute to differences in head impact kinematics from soccer heading. Within this context, Caccese et al. (5) could demonstrate that greater neck size and neck strength were associated with lower PLA and PRA of the head during heading by increasing a player's effective mass – i.e., the mass that opposes acceleration of the head and body when the ball strikes the head (see (1) for a comprehensive biomechanical explanation). However, since we did not directly assess players' heading technique or neck size/strength, these explanations are speculative and, thus, should be taken with caution.

This study contributes to the understanding of head impact kinematics of purposeful headers as a result of different in-game heading conditions. However, there are several limitations that should be acknowledged. While our focus on the, thus far, largely neglected group of semi-professional female soccer players might allow for comparisons of head impact kinematics between this population and female youth athletes (16) or women competing in lower levels of play, such as high school or college players (17, 23), a generalization of our findings to other populations (e.g., male athletes) proves difficult. Moreover, given that all players were part of the same team, specific team- or training-related factors (e.g., unique athletic training regimens) might constitute a source of bias and, in this sense, limit the generalizability of the present results. When comparing the herein reported impact magnitudes and their underlying factors to the ones observed by previous studies in female soccer athletes, differences in sensor types have to be considered. More specifically, Wu et al. (37) reported considerable differences in measured PLA and PRA values between headband, mouthpiece, and skin patch sensors. Therefore, between-study comparisons should be restricted to approaches, which also used skin patch sensors. However, given that the used device constitutes the most widely used wearable sensor model for the detection of head impacts in unhelmeted sports (29) and has been used in a variety of studies examining header-related impact kinematics in female players (30, 32), such comparisons are still possible. Ultimately, while we used a more comprehensive set of factors potentially influencing header-related head impact kinematics as compared to previous approaches (7, 12, 27), other variables, such as an individual's heading technique (13), players' neck strength (5), or ball velocity (8) prior to impact were not directly assessed. Therefore, the total variance explained by the models was limited (33.5% for PLA, 37.0% for PRA). Consequently, the additional consideration of these factors in future studies might alter the relative influence of the herein assessed variables on PLA and PRA due to intentional headers and, in this sense, allow for a more sophisticated understanding of the head's kinematic response as a result of routine soccer heading.

Conclusion

This study investigated the influence of a comprehensive set of factors on wearable-derived head impact kinematics resulting from purposeful soccer heading in an ecologically valid on-field setting. On average, our sample of semi-professional female players experienced greater peak linear and peak rotational accelerations of the head than previously reported in youth or college settings. Greater in-air distances of the ball prior to heading and a stronger ball reflection due to a header were associated with increased head impact kinematics. Moreover, subject-specific characteristics – potentially resembling inter-individual differences in heading technique and neck size/strength – were associated with both PLA and PRA of the head during headers. These findings add to the limited body of knowledge regarding differences in head impact magnitudes from in-game soccer heading and can be helpful to better understand the potential risk resulting from these RHI. However, future studies are needed to fully uncover the influence of different variables on head impact magnitudes of headers. These approaches should focus on investigating the combined effects of heading-related in-game factors, players' heading technique, muscle strength and anthropometric measures on the head's kinematic response to routine soccer heading.

Conflict of Interest

The authors have no conflict of interest.

Acknowledgements

All subjects provided written informed consent to participate in the study, which was approved by the ethical committee of the School of Medicine of the Technical University of Munich and conducted in accordance with the declaration of Helsinki.

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Data Availability

The raw data supporting the conclusions of this article will be made available by the authors, without undue reservation.

Summary Box

Semi-professional female soccer players experience greater head accelerations from heading than female youth athletes or women competing in lower levels of play. Headers strongly redirecting long distance shots generate the highest head accelerations. Subject-specific factors like an individual's heading technique might potentially reduce head accelerations from purposeful soccer heading.

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