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Exposure assessment for repeated sub-concussive head impacts in soccer: The HEalth and Ageing Data IN the Game of football (HEADING) study

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ABSTRACT

The purpose of this paper was to develop exposure estimates for repetitive sub-concussive head impacts (RSHI) for use in epidemiological analyses. We used a questionnaire to collect lifetime history of heading and other head contacts associated with training and playing football from 159 former footballers all members of the English professional football association. We used linear mixed effect regression with player as the random effect, to model the number of headers, blows to the head and head-to-head impacts as a function of potential exposure affecting factors, which were treated as the fixed effects. Exposure affecting factors included playing position, league, context of play (game vs training) and decade of play. Age at time of response to the questionnaire was also included in the models. In model results, playing position was important, with RSHIs being highest among defenders and lowest among goalkeepers. Players headed the ball more during games than in training, and when playing in amateur or youth leagues compared with semi-professional or professional leagues. The average number of reported head impacts declined linearly throughout the observation period (1949–2015). The derived final model for headers explained 43%, 9% and 36% of the between player, within player and total variance in exposure, respectively with good precision and predictive performance. These findings are generally in agreement with previously published results pointing towards the models forming a valid method for estimating exposure to RSHI among former footballers although some further external validation is still warranted.

1. Introduction

Head impacts such as those from heading in association football (soccer) are often referred to as repetitive sub-concussive head impacts (RSHIs) (Gysland et al., 2012). In contrast to concussion, RSHIs do not generally cause acute neurological symptoms, and therefore their clinical significance is more uncertain. The short and medium-term effects of RSHIs on human neurological health have been investigated (Bahrami et al., 2016), although they remain relatively ill-defined, and the long-term consequences of RSHIs are largely unknown (Pearce, 2016). Nonetheless, it has been suggested that RSHIs may result in persistent cognitive impairments and behavioural changes (McKee and Robinson, 2014) and recently published register-based studies suggested increased risks among former football players compared to the general population (Mackay et al., 2019; Ueda et al., 2023). A recent systematic review of sub-concussive injuries in sport concluded that there was insufficient to weak evidence of an association between RSHIs and neurological health (Mainwaring et al., 2018). To what extent the dynamics, the cumulative effect, and the location of the RSHIs have a role in modulating long term neurological impairment, is unclear from these data. The review also noted that studies that measured impact exposures used various indices, including linear acceleration, rotational acceleration, along with location and frequency of hits, with little consistency between studies.

The appropriateness of exposure indices for assessing the long-term

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risk from RSHIs in soccer players is uncertain. To further examine this, another recent systematic review focused on identifying those factors that determine the magnitude of head impact acceleration (Basinas et al., 2022). Exposure data from 27 observational and 33 experimental studies involving soccer play were included in standard statistical analysis approaches including student t-tests, correlation and simple linear regression analysis. Overall, the data from experimental studies appeared to be a poor proxy for normal play: in observational studies there was a close association between peak linear and angular accelerations, whereas in experimental studies these measures were less well correlated. The method of attaching the measurement accelerometer to the head was also seen to affect the magnitude of the measured acceleration. The linear acceleration experienced by female players and adults was on average higher than for male players and young people, respectively. Available evidence also suggested that the range of head acceleration during soccer playing is generally quite small and does not vary much between playing positions. In line with these findings, the authors suggested that for epidemiological studies of former soccer players the assessment of historical exposures to RSHI should be based on exposure metrics that rely on estimates of the cumulative number of RSHI over a playing career.

The HEalth and Ageing Data IN the Game of football (HEADING) Study explores the long-term cognitive function of around 200 former male professional footballers, aged 50 or over and who were members of the Professional Footballers' Association. In the present analysis, we used questionnaire data collected from 159 participants of the HEADING study to derive empirical exposure models capable of predicting historical cumulative exposures to RSHI. The elaborated models and predicted estimates from them will be used to estimate cumulative exposure to RHSI within the HEADING study.

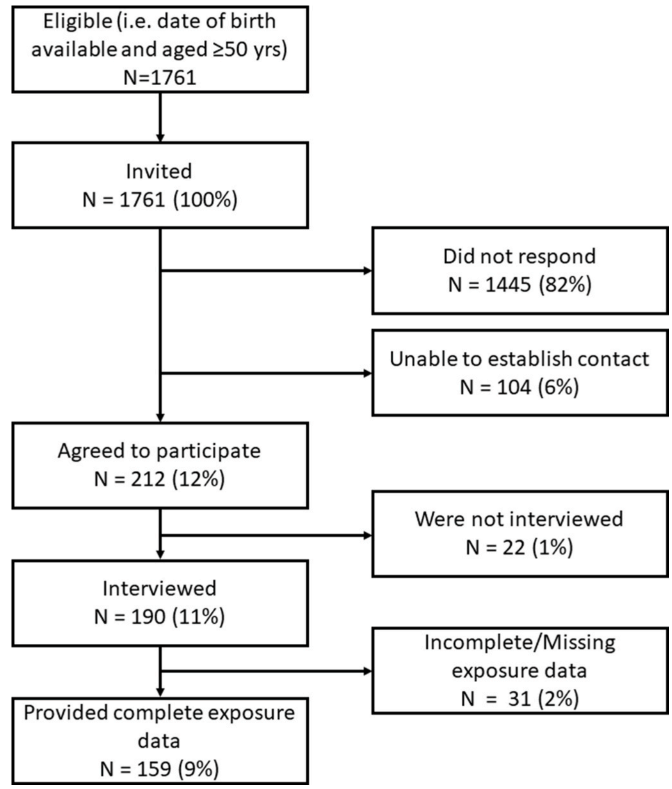

Fig. 1. Flow chart of the enrolment and data collection process.

2. Materials and methods

The HEADING study was designed to investigate the associations between concussion and/or RSHIs from heading the ball in soccer and cognitive function among former male professional soccer players in England. It is a cross-sectional study with a protocol for data collection similar to the BRAIN study of former professional English rugby players (Gallo et al., 2017), but data collection was simplified due to the restrictive measures put in place during the first years of the COVID-19 pandemic, with part of the assessment conducted online only (Seghezzo et al., 2021). A schematic representation of the enrolment and information collection process is provided in Fig. 1. Briefly, recruitment took place between July 2019 and December 2021. Current and former members of the Professional Footballers' Association (PFA – see https://www.thepfa.com/[thepfa.com]) who were known to be aged over 50 were invited by the PFA (for confidentiality reasons) to contact the study team if they were interested in taking part in the study. Some were invited by post and email (n = 1569), and the remainder by email only (n = 192). Of the 1761 invited to participate, 212 agreed to participate, and 190 of these were interviewed. Of the 190 interviewed, 159 provided complete exposure data. Data collection involved a personal interview using a standardised questionnaire and a health examination. At the end of the interview, which covered health, lifestyle and occupational characteristics, participants were asked to provide detailed information about their history of heading, head trauma and concussion while playing and training before, during and after their professional career. The telephone version of the BRAIN-Q test (BRAIN-Qt) already validated in the BRAIN study (Gallo et al., 2022; James et al., 2021), was used to assess exposure to concussion.

2.1. *Questionnaire administration*

For those participants recruited early in the data collection, the interviews and associated questionnaires were administered in person. However, due to COVID-19 restrictions, the administration of the questionnaires was switched to video communication software such as Zoom or Facetime. This was considered acceptable for the for collecting information on playing and concussion history, but there was some concern over the assessment of cognition using the Pre-Alzheimer Cognitive Composite (PACC) (Donohue et al., 2014). The reliability of the latter assessments was formally assessed in a sub-study, which found the online assessment was just as good as the in-person assessment provided the person facilitating the data collection had been suitably trained (Seghezzo et al., 2021).

2.2. *Playing history data*

During its development, the exposure assessment section of the HEADING questionnaire (see Online supplement for details) was piloted amongst groups of professional players. This was initially carried out using the coaching staff at Sheffield United football club and subsequently with the study Player Advisory Committee (PAC), which was formed from senior members of the PFA and Trustees of the PFA, as well as nominees from the Football Association. Members of the PAC provided feedback on the questionnaire until it was finalised. For both sessions, members of the HEADING study team administered the questionnaires.

Information on playing careers were collected separately for school, youth, professional/semi-professional, and amateur playing periods. A playing period was defined as a separate playing contract and participants were asked to fill a separate entry for each team for which they played. Players were asked to fill out a timeline of playing history including details of their experience at each club. Participants were also asked to provide information about play, including estimates of the typical number of games and training sessions they participated in each week, both in and out of each playing season. Estimates of the typical number of headers, blows to the head and (separately) head-to-head impacts they experienced during each playing session (i.e. game, training) were also provided. A playing season was assumed to be 38 weeks in length. A record of any prolonged absence from play along with the underlying reason and duration of absence was also provided.

2.3. Data curation and handling

The data on football career, including heading and other head impact information were collected initially in person, and then by Zoom with the onset of the pandemic. Prior to statistical analysis a thorough quality control of the responses of each participant was undertaken. Playing periods ranged in duration from less than a year to 24 yrs. Playing periods exceeding 10 years (n = 25) in duration were split into the decades they were associated with (to facilitate examining the importance of playing decade in any modelling). Decade of play was defined as the decade a playing period started. For any RSHI values reported as ranges the corresponding mid-point was used. In addition, league information was converted to numerical indicator to better define the league levels of play into eight categories (1 = Premier League; 2 = Championship; 3 = League One; 4 = League 2; 5 = Semi-professional; 6 = Amateur; 7 = Reserves/Youth and 8 = Overseas). Historical equivalent leagues were recognised where the name of the division had changed. Where league information was missing or unclear, contextual data (i.e. team played and calendar years) from the playing period was used to determine the league level. Playing level was also categorised into four groups: apprentice; amateur; semi-professional and professional. Where multiple levels were specified for a single period the highest level of play was used i.e. apprentice combined with professional was regarded as professional. In cases where playing level was omitted, historical information on leagues was used to fill any data gaps (see: http://www.englishfootballleaguetables.co.uk/). All playing periods with missing data on playing position (n = 34) or missing information on the frequency of RSHI during play (n = 174) were removed from the final dataset.

To allow the fit and performance of the elaborated models to be evaluated, prior to statistical analysis the dataset was randomised into two sub-sets of size equivalent to 70% and 30% of the total playing periods, respectively. The larger sub-set of the data was used to determine the predictive models, hereafter called the model training dataset, and the smaller sub-set was used to evaluate the model performance, hereafter called the model test dataset. Randomisation was made using SAS software SURVEYSELECT procedure (SAS Institute, 2020).

2.4. Data analysis

The number of headers, blows and head-to-head impacts, as reported on the questionnaire responses, followed a lognormal distribution and so prior to the initiation of the main analysis all data were log-transformed. Geometric means (GM) and geometric standard deviations (GSD) were used to summarise the exposure data presented alongside the relevant arithmetic means (AM).

Linear mixed effect regression (Peretz et al., 2002) was used to model the number of headers and other head impacts as a function of potential exposure affecting factors including decade of play (categorical), playing position (categorical), level of play (categorical), league (categorical) and context of event (games vs training). To account for possible differences in ability to recall, the age of the participant at the time of responding to the questionnaire, was included as a continuous variable in the model. Prior to the statistical modelling, all observations (n = 17, n = 13, and n = 24 for headers, blows and head-to-head impacts, respectively) with a value exceeding the mean of the distribution plus three standard deviations (i.e. 53.9, 11.2 and 7.4 for headers, blows and head-to-head impacts, respectively) were replaced by this value. Models were determined with player identifier as the random effect and potential exposure affecting factors as the fixed effect. Association between fixed effects and RSHI impacts were first examined at a univariable level. Amid small numbers and very similar effects and to preserve degrees of freedom for the multivariate analysis, utility players (i.e. those frequently playing in more than one position) were merged with forwards and league 2 players with league 1 players. Multivariable model build followed a forward selection approach where variables entered the model based on level of significance and improvement of fit as assessed by the Akaike and Bayesian information criteria. Model adequacy was assessed through influence diagnostic and residual plots. In all models, estimation of variance components was based on the restricted maximum likelihood method. The robustness of the derived model coefficients was examined in a series of sensitivity analyses. These included excluding all observations with reported typical number of headers exceeding 29 (the 95th percentile of the distribution of reported headers), removing all observations sourcing from goalkeepers, and excluding all observation sourcing from subjects aged above 74.5 years (the 90th percentile of the age distribution of all participants) or above 61.27 years of age (the median of the age distribution of all participants) to examine for the presence of effects of recall. Pearson and, when appropriate, Spearman correlation coefficients were also used to describe associations between the observed values of the different types of head impacts and potential exposure affecting factors.

The derived model equations were used to predict geometric mean numbers of RSHIs per event by position, playing level and decade of play. Separate estimates for games and training sessions were determined. All model predictions were made assuming the participant's age was equal to the median of all study participants included in the dataset (i.e. 61.27 years).

To evaluate its overall fit, precision and predictive performance, the final model was re-fitted on the test dataset and the results, including predictions, were compared to those from the model training dataset. Comparisons involved estimating the Proportion Change in Variance (PCV) overall, between-players and within players, and after model predictions the Root Mean Square Error (RMSE) and the Mean Absolute Error (MAE). The MAE was calculated as the mean absolute difference between the predicted and absolute values whereas the RMSE was estimated as the square root of average of the square difference between the predicted values and the actual values. The MAE is a measure of the size of the residual in a dataset whereas the RMSE is an indicator of the average distance of observed data points from the fitted model line.

All data were analysed using the SAS statistical software version 9.4 (SAS Institute, 2020).

3. Results

The basic characteristics of the model training and test datasets are shown in Table 1. Overall, 1888 observations representing different periods of play across the 159 participants were available, of which, following randomisation, 1322 were allocated to the model build/training dataset and 566 to the evaluation/test dataset. Slightly more players were present in the model dataset albeit with no further systematic differences between the two datasets across all the exposure affecting factors and/or outcome head impact numbers included. Of all 1888 observations included, 43% were sourced from defenders with the other half almost equally distributed among forwards (25%) and midfielders (28%). The vast majority (83%) of career playing by the study participants occurred between 1970 and 2000 and were mostly at a professional level (67%).

Table 2 summarizes the distribution characteristics of the number of different types of RSHIs across relevant exposure affecting factors. The geometric mean number of reported head impacts was highest among defenders (GM = 13.7; GSD = 2.7) and lowest among goalkeepers (GM = 0.36; GSD = 13.7). Goalkeepers also reported the fewest head-to-head collisions compared to players in other positions. For blows to the head, the fewest occurred among midfielders (Table 2). Both blows to the head and head-to-head collisions were most frequently reported among forward/utility players (AMs of 2.78 and 1.26, respectively). Players reported, on average, that they headed the ball more during games than during training sessions (GM of headers per session: 10.95 vs 6.88, respectively) and when playing in semi-professional or professional

Table 1
Basic characteristics of the model training and test datasets (n = 1888). Data were based on self-reported information from 159 male former professional English football players.

Characteristic	Model training dataset	Model test dataset
n	1322	566
k	157	148
Age of players, mean (SD)	62.6 (8.8)	62.2 (8.0)
Event		
Match	675 (51.1)	293 (51.8)
Training	647 (48.9)	273 (48.2)
Position		
Defender	554 (41.9)	257 (45.4)
Forward	340 (25.7)	139 (24.6)
Goalkeeper	31 (2.4)	13 (2.3)
Midfield	374 (28.3)	149 (26.3)
Utility	23 (1.7)	8 (1.4)
Decade of play		
≤1950	19 (1.4)	5 (0.9)
1960	113 (8.6)	37 (6.5)
1970	296 (22.4)	135 (23.9)
1980	463 (35.0)	204 (36.0)
1990	337 (25.5)	137 (24.2)
≥2000	94 (7.1)	48 (8.5)
League		
Reserves/Youth	61 (4.6)	27 (4.8)
Amateur	93 (7.0)	46 (8.1)
Semi-professional (Leagues < league 2)	280 (21.2)	123 (21.7)
League one or two	367 (27.8)	181 (32.0)
Championship	270 (20.4)	97 (17.1))
Overseas leagues	34 (2.6)	14 (2.5)
Premier league	217 (16.4)	78 (13.8)
# of headers per game, AM (SD)	14.2 (13.3) 0–100	13.5 (11.1) 0–100
# of blows per game, AM (SD)	1.3 (3.3) 0–30	1.2 (2.6) 0–30
# of head-to-head contacts per game, AM (SD)	1.1 (2.1) 0–15	1.2 (2.2) 0–15

n = number of playing periods; k = number of players.

leagues (range of GMs: 8.34–9.53 headers per session) compared to amateur and youth leagues (range of GMs: 7.21–7.28 headers per session). Correlations between the different types of RSHI ranged from low ($r_{spearman}$ of 0.18 between headers and blows) to moderate ($r_{spearman}$ of 0.68 between blows and head-to-head impacts).

Table 3 presents the final multivariable model on the associations between position, league, decade of play, age and playing context and the number of reported headers per training or play event. The corresponding models for blows to the head and head-to-head impacts are presented in the online supplement (Table S1). Overall, the model for headers explained more than 42% of the variation in reported headers between players and 36% of the total variation in reported number of headers. Forward/utility and midfield players reported heading the ball less per session than defenders by a factor 0.83 and 0.67 (Table 3, reported GMR values), respectively, which was statistically significant for the latter. Playing in the English Premier League was associated with statistically significantly greater number of headers compared to semi-professional, amateur, and youth leagues. The number of headers appeared to significantly decrease with an increased decade of play whereas training was associated with a reduced number of headers by a factor 0.66 (Table 3, GMR values). An increased participant age at reporting was associated with a decreased number of reported headers.

The models for blows to the head and head-to-head impacts both explained approximately 13% of the total variability in exposure to head impacts. League and position remained important determinants of the reported frequency of these head impacts albeit with differences in the reported patterns compared to headers. Similarly, the number of reported impacts for blows and head-to-head impacts appeared to increase with an increased decade of play although this trend was not statistically significant.

Sensitivity analysis by excluding all observations with reported number of headers ≥29 (the 95th percentile of the distribution of reported headers) or those from goalkeepers showed no change in direction of effects and very little change in the effect sizes of the model for headers (data not shown). Excluding all observations from participants aged 74.5 and above and 61.27 and above did also not produce systematic differences in the main model results, although in the latter case no effect of participant age at responding was observed (data also not shown).

The results of the comparison of the fit and predictive ability of the model when fitted with the training and test data respectively are shown in Table 4. In general, model performance was relatively similar, with the training dataset explaining slightly more variability in exposure. Small differences were also seen when looking at the estimated RMSE and MAE values, which were generally low, indicating the presence of small model errors in both datasets.

The predictions from the final models for all types of RSHI, across all relevant strata (i.e. position, league, decade, and context) for estimating exposure within the HEADING study may be obtained by request to the authors.

Table 2
Distribution of reported per session average number of headers, blows to the head, and head-to-head collisions by position, league and context of play. Results of the model training dataset are shown that are based on self-reported data from 157 former professional English players.

Category	n	k	# of headers			# of blows to the head			# of head-to-head collisions		
			AM	GM (GSD)	Range	AM	GM (GSD)	Range	AM	GM (GSD)	Range
Position											
Forward/utility	363	50	13.30	9.92 (2.5)	0–100	2.78	0.43 (16.4)	0–30	1.26	0.23 (14.8)	0–9
Goalkeeper	31	6	2.06	0.36 (13.7)	0–10	0.81	0.20 (7.0)	0–4	0.10	0.01 (14.5)	0–0.3
Midfield	374	62	9.02	5.17 (5.1)	0–40	0.60	0.07 (13.3)	0–6	0.90	0.06 (15.8)	0–10
Defender	554	85	18.80	13.65 (2.7)	0–100	0.82	0.18 (9.2)	0–15	1.05	0.17 (11.5)	0–15
League											
Reserves/Youth	61	30	11.70	7.21 (4.3)	0–40	1.02	0.21 (11.9)	0–6	0.58	0.09 (16.5)	0–3
Amateur	93	30	13.25	7.28 (5.9)	0–40	0.48	0.06 (14.3)	0–3	0.50	0.07 (10.9)	0–10
Semi-professional (Leagues < league 2)	280	80	13.32	8.94 (3.8)	0–40	1.09	0.18 (10.3)	0–12	1.01	0.11 (15.6)	0–10
League one or two	367	107	15.53	9.53 (3.6)	0–100	1.29	0.17 (14.3)	0–30	1.14	0.14 (15.9)	0–15
Championship	270	84	13.95	8.74 (3.6)	0–100	1.48	0.23 (12.4)	0–30	1.36	0.19 (13.4)	0–15
Overseas leagues	34	19	16.29	8.38 (3.3)	0–100	2.24	0.22 (24.9)	0–20	1.3	0.17 (25.0)	0–10
Premier league	217	74	13.96	8.34 (4.9)	0–100	1.74	0.21 (13.4)	0–30	0.94	0.14 (12.4)	0–15
Context session											
Match	675	154	15.7	10.95 (2.7)	0–100	1.32	0.18 (13.1)	0.-30	1.06	0.13 (14.7)	0–15
Training	647	148	12.8	6.88 (2.7)	0–100	0	–	0	0	–	0

N = number of observation periods; K = number of players, AM = Arithmetic mean, GM = Geometric mean, GSD = Geometric Standard deviation.

Table 3
Effects of playing characteristics on the average number of reported headers per training or play event.

Parameter	n	*β*	*e*	*GMR*	*p*
Intercept		2.73	0.12	15.38	<.0001
Position					
Forward/utility	363	−0.18	0.13	0.83	0.15
Goalkeeper	31	−3.93	0.38	0.02	<.0001
Midfield	374	−0.40	0.12	0.67	<0.001
Defender	554	Ref			
League					
Reserves/Youth	61	−0.25	0.15	0.78	0.10
Amateur	93	−0.46	0.14	0.63	0.001
Semi-professional (Leagues < league 2)	280	−0.22	0.10	0.81	0.03
League one or two	367	−0.04	0.09	0.96	0.66
Championship	270	0.05	0.10	1.05	0.62
Overseas leagues	34	−0.28	0.18	0.76	0.13
Premier league	217	Ref			
Decade of play (starting)					
≤1950	19	0.27	0.25	1.31	0.29
1960	113	0.30	0.13	1.35	0.02
1970	296	0.10	0.08	1.10	0.20
1990	337	−0.09	0.07	0.92	0.23
≥2000	94	−0.29	0.13	0.75	0.02
1980	463	Ref			
Context					
Training	647	−0.41	0.05	0.66	<.0001
Match	675	Ref			
Age (continuous)		−0.04	0.01	0.96	<.0001
$_{bp}\sigma^2$(naive estimate)		0.67 (1.24)	0.09		
$_{wp}\sigma^2$(naive estimate)		0.76 (0.82)	0.03		
Explained variability					
PCV_{bp}		42.6%			
PCV_{wp}		9.3%			
PCV_{total}		36.0%			

n = number of observations with specific characteristic; β = regression coefficient for log-transformed head impact (header) data; e = standard error; p = p-value; $bp\sigma^2$ = between-player variance; $wp\sigma^2$ = within-player variance; PCV_{wp} = Proportion change in variance within players; PCV_{total} = Proportion change in total variance; GMR = Geometric Mean Ratio. Naïve estimates are derived by a model with only the random effects included.

4. Discussion

We have developed empirical exposure models to predict historical exposures to RSHIs among former male soccer players in England. Our approach is based on our earlier analysis, which indicated that the magnitude of the acceleration experienced when heading a ball was similar regardless of other factors such as playing position (Basinas et al., 2022). Consequently, we tailored our approach to enable estimates of the cumulative number of head impacts for study participants of epidemiological studies. The final models include playing position, league, decade played, context (play versus training) and age, and separately predicts number of RSHIs in each playing or training event from headers, blows to the head and head-to-head contacts. These data can then be combined with data on the players' careers to estimate lifetime cumulative exposures, although we recommend keeping the cumulative number of the three types of RSHIs separate because the magnitude of acceleration in each case is likely different.

The models show that goalkeepers infrequently head the ball during play, and midfield players head the ball less frequently than other outfield players. Defenders were found to head the ball most frequently compared to all other player categories. Recently published observational data collected by the English Football Association (FA) corroborated these findings (FA, 2021). In these data, collected between the period 2013–2021, defenders were observed to head the ball almost twice as much as other players (average 7.5 vs 3.6 to 4.5 per game). Similar findings were also reported among semi-professional French players where average headers per hour were found to be highest among center backs followed by forwards (Cassoudesalle et al., 2020). A study of US college age players that included males in their study population also reported defenders experienced somewhat higher numbers of head impacts compared to players in other positions (Reynolds et al., 2017a). However, in this study any type of head impact, including impacts other than headers, were accounted for in this comparisons. Predicted estimates from our models for Premier league players for the period after 2000 correspond to 7.7, 9.6 and 11.5 headers per game for midfield, forward/utility and defenders, respectively. These results are higher than the corresponding values of 3.7, 4.9 and 7.0 reported for the period 2013–2021 in the FA report (FA, 2021). On the other hand, for the same period our championships predictions (5.4, 6.6, and 8.0 headers per game for midfield, forward/utility and defenders, respectively) seem more comparable to those reported by the FA (4.4, 6.2, 9.3 headers per game for midfield, forward/utility and defenders, respectively). Our sample included only one player that had a career extending beyond 2010 and so any implementation of our models for periods not covered by the data should be made with caution.

The league of play, decade of play and context were, in our study, important exposure predictors for the frequency of headers performed. Previous results from US observational studies suggested somewhat conflicting results in relation to the difference in frequency of head impacts between practice and gaming sessions (Press and Rowson, 2017; Reed et al., 2002; Reynolds et al., 2017a, 2017b; Rich et al., 2019). However, it is important to note that most of those studies collected information on head impacts for the purpose of measuring impact acceleration, where typically all impacts above a certain threshold of acceleration are registered. In addition, several of those studies involved measurements exclusively among female players (Press and Rowson, 2017; Rich et al., 2019), and all involved young non-professional players of college or youth age. Sex is an important difference for RSHI impact and existing data also suggest important differences in head impact patterns between youth and older aged players (Basinas et al., 2022). League and decade of play have seen little study before. In our data set, there were fewer predicted headers for players in the amateur game, compared to fully professional players, with semi-professional and reserve/youth players predicted to have the number of headers between these two. There were also fewer headers predicted for play during later decades of play compared to the 1950s and 60s. In its recent training guidance the English Football Association (FA) suggested that the average number of headers performed per game is higher in leagues lower than the premier league with the highest number observed in players in league 2 (range of 5.1–10.1 vs 3.7–7.0 headers per game in the premier league) (FA, 2021). Our models suggest little differences between Premier league, championship and leagues 1 and 2. However, our grouping of leagues differs slightly from the one used in the FA report. In addition, playing style of English football has evolved through the

Table 4
Comparison of model results using the model training and test datasets.

Dataset	n	AIC*	BIC*	PCV_{bp}	PCV_{wp}	PCV_{total}	RSME	MAE
Training	1322	3739.7 (3832.2)	3745.8 (3838.3)	42.6	9.3	36.0	1.20	0.78
Test	566	1554 (1664.1)	1560 (1670.1)	46.9	9.4	40.7	1.02	0.73

n = number of observations; AIC = Akaike information criterion; BIC = Bayesian information criterion; PCV_{bp} = Proportion change in variance between players; PCV_{wp} = Proportion change in variance within players; PCV_{total} = Proportion change in total variance; RMSE = Root Mean Square Error; MAE = Mean absolute error.

decades (Bush et al., 2015), which could potentially explain differences observed.

Overall, estimated variability in the frequency of head impacts is larger between than within players – irrespective of the type of impact involved (see naïve estimates in Table 3 and Table S1). Differences in exposure to RHSI, as determined by frequency, arise primarily from factors that are different between players but consistent over time. Such factors include playing position and league, for which generally remain stable for players for longer periods of time. The fact that our model explains almost half of the between players variance in header frequency implies that the included fixed factors are good predictors of those differences. On the contrary, changes within the career of individual players (e.g. in playing league) appear to occur less frequently and to have negligible effect on the variability in exposure. The total variance explained by our final model for headers was approximately 36% whereas the corresponding value for blows to the head and head-to-head collisions were approximately 13%. These performances are in line with what we see from similar exercises performed for chemical and physical exposures where proportions of explained variance typically range between 10 and 40% (Basinas et al., 2014; Peters et al., 2011; Stokholm et al., 2020). The lower variance explained for blows to the head and head-to-head impacts suggest that potential important exposure affecting factors for these RSHIs may remain unaccounted for by our final models. Such impacts according to our data occur less frequently compared to headers accounting, according to our data, for less than 10% of the total impacts received by a player during a typical session. Previous experimental results suggested that players experience higher peak linear acceleration (PLA) values during head-to-head collisions compared to ball-to-head impacts (i.e. 300 m/s^2 at 2.5 m/s impact speed and around 700 m/s^2 at 3.5 m/s impact speed for head-to-head collisions vs $\sim$150 m/s^2 at 8 m/s impact speed for ball-to-head impacts, respectively) (Hanlon and Bir, 2010) suggesting that these differences need to be accounted for when calculating the cumulative exposure across a player's career. In observational studies, however, the above patterns are far from clear. Amongst collegiate female players median PLA from head-to-head contacts were reported to be 350 m/s^2 compared to around 200 m/s^2 during headers from passes (Lamond et al., 2018), but other studies, primarily among youth players, suggest PLA associated with non-header-to-ball impacts to be much lower compared to headers events (Nevins et al., 2017; Sandmo et al., 2019; Saunders et al., 2020). At present observational data comparing the acceleration of blows to the head and/or head-to-head impacts with the acceleration of head to ball impacts during actual adult professional play are yet to become available (Basinas et al., 2022). Such information are essential for allowing relative differences in PLA between different types of impacts to be accounted for when calculating the cumulative burden of head impacts across the career of former professional players.

The overall participation rate into our study was 11% which raises a prospect for selection bias by excluding participants with severe cognitive impairment. In addition, the playing histories and reported RSHI frequencies are subject to potential bias originating from the ability of the participants to recall the past. Such information bias can lead to misclassification effects potentially affecting the estimated exposure-response relationships in epidemiological analysis. In principle, imperfect recall that is not subject to disease status (i.e. non-differential misclassification) will bias risk estimates towards the null. Recall that is differential to the status of disease however, can bias risk estimates either towards or away from the null (Pearce et al., 2007). To tackle the potential presence of recall issues we have taken several measures, both at a design (i.e. exposure assessment completed at the end of the interview to keep participants blind to concussion status and level of exposure to RSHI), and modelling/statistical analysis stage including removing outliers when determining prediction models, and adding age at time of data collection as a parameter in the developed models. The effects of the main model remained directionally robust when all data from subjects aged $\geq$74.5 years and $\geq$61.27 years were excluded from the modeling process which suggests limited effects in terms of cognition. In our study, it is unlikely that any selection or recall has been differential in nature and thereby any such bias, if present will likely result in attenuating the relationships between the exposure and the outcomes of interest towards the null. By modelling exposure based on similar exposure groups defined by key exposure affecting factors we allow exposure to be assigned at a group level, limiting thereby the presence of bias on the associations between exposure and health outcomes due to the introduction of the so called "Berkson error" (Armstrong, 1998). Nevertheless, the presence of selection and/or recall bias cannot be excluded and in the future, we aim to further validate the predicted exposure estimates and the participants recall by a) using the statistics of historical playing careers to evaluate the participants ability to recall their career and b) by performing direct validation exercises on the accuracy of reported and modeled head impact number estimates using video recordings of historical games. The intent will be to calibrate model results based on those findings.

The developed models can be used to retrospectively assign RSHI exposure estimates to the participants of HEADING and similar studies on the basis of their career characteristics in the prospect of estimating their cumulative whole life burden to RSHI. Although, the models were developed for, and using information from, former male players in England, we see no reason why they should not be used in epidemiological studies of soccer male players in countries other than the United Kingdom. However, given the differences in playing style between England and European or other continent's teams we would not recommend using the models in these situations without first undertaking some additional validation checks. In addition, the frequency and intensity (i.e. Peak Linear Acceleration) of head impacts have been reported to be systematically different between genders (Basinas et al., 2022). In general, males are reported to experience higher frequency of headers per hour than females whereas acceleration from heading is reported to be much higher among females as a result of a lower muscle neck strength. As a result we do not recommend use of our models on studies of female population without a prior extensive validation check against data from such populations.

5. Conclusions

We have developed empirical exposure models that enable us to predict exposure to RSHI on the basis of the context, position, decade, and league involved. The derived effects and impact estimates across positions are in agreement and of the same magnitude of recently published data concerning heading statistics among English football leagues. Exposure estimations therefore using the developed models a valid measure for such exposures, although further work is required on some aspects of their external validity. The models and related predictions will be used to estimate the cumulative lifetime exposure to heading and other head impacts from soccer within the HEADING study, a cross-sectional epidemiological study among former professional English footballers. The authors are happy to make the models and exposure estimates available to other *bone fide* researchers upon request.

Conflicts of interest

The authors declare no conflict of interest. The funders had no role in the design of the study; in the collection, analyses, or interpretation of data; in the writing of the manuscript; or in the decision to publish the results.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.ijheh.2023.114235.

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