Concussion and long-term cognitive function among rugby players—The BRAIN Study

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Abstract
Objective: The BRAIN Study was established to assess the associations between self-reported concussions and cognitive function among retired rugby players.

Methods: Former elite-level male rugby union players (50+ years) in England were recruited. Exposure to rugby-related concussion was collected using the BRAIN-Q tool. The primary outcome measure was the Preclinical Alzheimer Cognitive Composite (PACC). Linear regressions were conducted for the association between concussion and PACC score, adjusting for confounders.

Results: A total of 146 participants were recruited. The mean (standard deviation) length of playing career was 15.8 (5.4) years. A total of 79.5% reported rugby-related concussions.
INTRODUCTION

Since chronic traumatic encephalopathy (CTE) was first described as a nosological entity,1,2 scientific attention has focused on the long-term sequelae of sports-related mild traumatic brain injury, or concussion.3 Neuropathological changes suggestive of CTE have been reported in boxers,4 American football players,5 ice hockey players,6 football (soccer) players,7,8 and rugby players.8,9 However, these reports are mostly based on case series, with limited sample sizes. The findings among American footballers showed also that length of career was associated with more severe neuropathology,10–12 suggesting a possible role of subconcussive head impacts. Reviews of current epidemiological evidence suggest an increased risk of lower cognitive function in previously concussed athletes, but the findings are inconsistent.13 Conversely, the health benefits of physical activity and participation in sports, including a protective effect against cognitive decline, are well established.14 What is currently unclear is to what extent the sports benefits outweigh any potentially harmful effects of concussion, and whether such hazards are sport-specific.

In rugby union players, little evidence is currently available on the long-term cognitive consequences of concussion. One study found an association between concussion and lower cognitive function, but the effect size was small and there were multiple comparisons.15 Conversely, the same association was not found in another study, possibly due to lack of power to detect small effects.16 A third study found no association, although mild cognitive disorders were found to be more common in the rugby players compared to other non-contact athletes.17

The aim of the Brain Health and Healthy Ageing in Retired Rugby Union Players (BRAIN) Study was therefore to assess the long-term association between concussions and cognitive function among retired elite rugby players.

METHODS

The design of the BRAIN Study has been described in detail previously.18 Briefly, this is a cross-sectional study recruiting former elite male rugby union players aged 50+ years from two sources: former Oxford/Cambridge University players previously recruited in a study conducted in the Centre for Sport, Exercise and Osteoarthritis Research Versus Arthritis at the University of Oxford, who had consented to be re-contacted;19 and all individuals listed on the England Rugby Internationals Club (ERIC) database—an organization of current and former England international players. We estimated that by recruiting 150 former players, considering that the standard deviations (SDs) of the psychometric tests are in the range of 8% to 15% of the absolute value, the study would have more than 95% power to detect a 10% difference, and 80% power to detect a 7% difference in psychometric test scores between exposed (to concussion) and non-exposed participants.18

Those invited were given the choice to be assessed in a clinic (London, Manchester, or Bristol), or at home. The assessment included questions on rugby playing career, occupation, lifestyle factors, cognitive ability, and self-reported history of concussion.18 Participants who could not attend an assessment completed a postal questionnaire; those cognitively impaired were included in the study and assessed in person with the assistance of a close family member. All participants signed an informed consent. The study was approved by the Ethical Committee of the London School of Hygiene and Tropical Medicine (EC/11634) and further approved by the other participating institutions’ ethical committees. A meeting was held with the representatives of participants to discuss how to increase response rates and how to communicate results to participants and the general public.

EXPOSURE ASSESSMENT

Information on concussions was collected at the end of the assessment to avoid observer bias, using the BRAIN-Q tool.20 This tool was developed to overcome some of the limitations of existing tools, which are not designed specifically for sports-related concussions, and do not always provide a clear-cut definition of concussion (which is particularly relevant for people who have been exposed to concussion in a context of changing definitions, such as the sports arena). In addition, the BRAIN-Q was designed to maximize recall in different stages of the playing career. Participants were asked to report the number of concussions they suffered after being given the following definition of concussion:5,18

concussion(s). No association was found between concussion and PACC ($\beta$ –0.03 [95% confidence interval (CI): –1.31, 0.26]). However, participants aged 80+ years reporting 3+ concussions had worse cognitive function than those without concussion ($\beta$ –1.04 [95% CI: –1.62, –0.47]).

Conclusions: Overall there was no association between concussion and cognitive function; however, a significant interaction with age revealed an association in older participants.

KEYWORDS

cognitive function, occupational epidemiology, rugby, sports-related concussion
An alteration in brain function, caused by an external force. Symptoms include: a decreased level/loss of consciousness; memory loss (before or after the injury); weakness/temporary paralysis; loss of balance; change in vision (e.g., blurriness, double vision); co-ordination difficulties; numbness; decreased sense of smell; difficulty understanding what others are saying; difficulty communicating with others; confusion, disorientation, or slowed thinking. Loss of consciousness is not required for a concussion to be diagnosed.

They were then invited to complete a “life timeline” with the most significant milestones of their youth and professional career, and to review their recalled concussions in each of the periods, confirming the information given. For each concussion, additional details were collected, for example, hospitalization. Two variables were then derived: the total number of rugby-related concussions, categorized into “no concussion,” “low concussion (1 or 2),” and “high concussion (3+)”; and the rugby-related concussion density defined as the total number of concussions divided by the time interval in years (participants with 2+ concussions only). Given the accumulation of new evidence since the analysis plan for the BRAIN Study was finalized, length of rugby career was added to the analysis as an independent exposure, in addition to number of concussions.

### 2.2 Assessment of cognitive function

The primary outcome measure was an adapted version of the Alzheimer’s Disease Cooperative Study–Preclinical Alzheimer Cognitive Composite (ADCS-PACC). The PACC includes: (1) The Total Recall score from the Free and Cued Selective Reminding Test (FCSRT; 0–48 words); (2) The Delayed Recall score on the Logical Memory-II subtest from the Wechsler Memory Scale (0–25 story units); (3) The Digit Symbol Substitution Test score from the Wechsler Adult Intelligence Scale–Revised (0–93 symbols); (4) The Mini-Mental State Examination (MMSE; 0–30 points). The FCSRT was replaced with the total score of the 12-item Face–Name Associative Memory Exam (FNAME-12), 0 to 96 points, which is similar in terms of testing immediate and delayed recall, as it showed evidence of convergent validity with the established paired associative memory task, FCSRT (Pearson r 0.32, P < 0.05). All tests were administered and scored according to the standard procedures. The test scores of the four components of the PACC were standardized to create z-scores based on the overall BRAIN Study sample and averaged. At least three tests had to be completed to create a PACC score, one of them being the MMSE.

### 2.3 Covariates and potential confounders

Potential confounding variables and their categorization were pre-specified in the analysis plan. Age in years was recorded at the time of the assessment. Highest educational qualification was classified into: A-level or below; university degree; post-graduate degree. Occupational history was categorized according to the International Standard Classification of Occupations (ISCO)-88, using the job held with the longest duration, into “legislators, managers and senior officials,” “professionals,” and “other” (including both skilled and unskilled manual labor). Tobacco smoking and alcohol drinking were classified as current/former/never. Diagnoses of hypertension and diabetes were recorded. Height and fully dressed body weight were recorded during the assessment for calculating the body mass index (BMI). Length of rugby career and predominant position played were recorded and classified as back (back 3, midfield, scrum half) or forward (back row, second row, front row). Early-life intelligence was assessed using the National Adult Reading Test (NART), 0 to 50 points.

### 2.4 Statistical analysis

The potential for selection bias was explored in the sample recruited through the University of Oxford by comparing the basic information...
of those who agreed and those who declined to take part in the study.

Scores of cognitive tests were coded as zero if the participant did not undertake them because he was cognitively unable to do so. Missing values for cognitive tests (except the MMSE), exposure variables, and covariates were imputed using multiple imputation by chained equations (MICE), that is, fully conditional specification, creating 10 imputed datasets. Individual imputation models used logistic regression for binary variables, ordinal logistic regression for ordered categorical variables, and multinomial regression for unordered categorical variables. For continuous variables with missing values, predictive mean matching was used, with five nearest neighbors, to address potential issues with non-normality.

Linear regression models were conducted for the PACC score, with the cumulative number of concussions ( ordinal categorical as the main exposure variable; concussion density, and length of career were also analyzed as independent exposure variables. The analyses were adjusted for prespecified potential confounders: age (continuous), education, occupation, smoking, alcohol, BMI (continuous), medical history, rugby position, NART, and study assessor. An interaction between concussion history and age in 10-year age bands was sought. The analyses were repeated modeling age using restricted cubic splines, and results were displayed graphically.

To compare the cognitive function of the study participants with a convenience sample of cognitively normal individuals, a predicted score was estimated for each participant for the main cognitive tests and compared to those obtained by each BRAIN participant, and displayed graphically. These predicted values were generated using the National Alzheimer’s Coordinating Center Uniform Data Set (UDS) normative calculator, which is based on data from 3268 clinically cognitively normal older subjects, by inputting age, years of education, and sex of each BRAIN participant (all were male) into the model.

The following equations were used:

\[
\text{Predicted MMSE} = 28.41 + (-0.48 \times \text{Sex}) + (0.14 \times \text{Education}) + (-0.02 \times \text{Age})
\]

\[
\text{Predicted LMDR} = 9.13 + (-1.39 \times \text{Sex}) + (0.41 \times \text{Education}) + (-0.026 \times \text{Age})
\]

\[
\text{Predicted DigitSubstitution} = 71.23 + (-3.15 \times \text{Sex}) + (1.12 \times \text{Education}) + (-0.56 \times \text{Age})
\]

The predicted scores of the FNAME test were taken from a model derived from a study of 216 cognitively normal Greek individuals. These predicted scores were derived from inputting age of each BRAIN participant; however, this model was limited to only those between the ages of 60 and 85 with at least 6 years of education, thus not entirely comparable with the BRAIN sample. The following equation was used to calculate predicted FNAME scores:

\[
\text{Predicted FNAME} = 70.30 + (-0.23 \times \text{Age})
\]

The predicted scores were then compared to the scores obtained by each BRAIN participant, and displayed using box and whisker plots.

Sensitivity analyses were carried out after excluding participants with MICE imputed values, excluding cognitively impaired participants (MMSE < 25/30), and excluding adjustment for the study assessor from the multivariable model.

3 | RESULTS

Of the 205 invitations sent by the University of Oxford, 190 were valid, from which 113 participants were recruited (response rate: 59.5%). Of the 104 invitations sent to the ERCI participants (103 valid), 33 participants were recruited (response rate: 32.0%). The overall response rate was 49.8% (Figure S1 in supporting information). An analysis of non-respondents comparing the 77 participants invited by the University of Oxford but not recruited in the BRAIN Study with the 113 recruited from the same source showed no systematic differences between the two groups except that 62% of those recruited reported a concussion in the original study versus 51% of those not recruited (P = 0.04; Table S1 in supporting information). The difference in response rate might be because participants recruited through the University of Oxford were already engaged in rugby-related research, and there was updated contact information available.

The main analyses were based on 143 participants, excluding those assessed remotely. MICE imputations were performed on the missing data (N = 7). The demographic and playing characteristics of the sample are shown in Table 1. The median age (p25–p75) of the sample was 70 years (61–77). The sample was highly educated. The mean (SD) length of playing career was 15.8 (5.4) years; the position played by the participants was grouped into backs (55%) and forwards (45%).

A total of 116 (80%) respondents reported at least one rugby-related concussion. Among the concussed, the number of rugby-related concussions varied between 1 and 25, with a median (p25–p75) of 2 (1–4). The number of rugby-related concussions was not associated with position played (P = 0.75; Figure S2 in supporting information), or with length of career (Figure 1). Considering total concussion, only 27 participants (18%) reported none.

The findings for the individual tests of the PACC are reported in Table 2. PACC scores by age groups are shown in Figure 2. Age (Pearson r = 0.58, P < 0.001) and NART score (Pearson r = 0.34, P < 0.001) were found to be positively correlated with PACC. Predicted test scores were displayed in Table S2 in supporting information, and shown in Figure S3 in supporting information: former rugby players scored lower than predicted for logical memory but better than predicted for immediate and delayed recall. Interestingly, this advantage seems to be lost with age, as in both cases those in the older age group scored lower than the predicted scores.

An interaction between the effects of concussion history and age was evident (P = 0.003); therefore, the analyses were also repeated by age group (Table 3). Overall, there was no association between concussion and cognitive function measured by the PACC (β-coefficient for high vs. no concussion −0.03 [95% confidence interval (CI): −0.31,
|                          | No concussion | Low concussion \((1-2)\) | High concussion \((3+)\) | All          |
|--------------------------|---------------|--------------------------|--------------------------|--------------|
| **Number of concussions, median (p25, p75)** | 0             | 2 (1, 2)                 | 4 (3, 6)                 | 2 (1, 4)     |
| **Concussion density, median (p25, p75)**     | 0             | 0.40 (0.29, 1)           | 0.46 (0.33, 1)           | 0.45 (0.31,1) |
| **Age (years), median (p25, p75)**            | 76 (65, 82)   | 71 (61.5, 76.5)          | 67.5 (60, 74)            | 70 (61, 77)  |
| **Education, N (%)**                            |               |                          |                          |              |
| A-level or below                | 7 (23.3)      | 16 (30.7)                | 15 (23.4)                | 38 (26)      |
| University degree               | 14 (46.7)     | 21 (40.4)                | 27 (42.2)                | 62 (42.5)    |
| Post-graduate degree            | 9 (30)        | 15 (28.8)                | 22 (34.4)                | 46 (31.5)    |
| **Occupation, N (%)**                        |               |                          |                          |              |
| Legislators, senior officials, managers | 16 (53.3)     | 19 (36.5)                | 25 (39)                  | 60 (41.1)    |
| Professionals                    | 8 (26.7)      | 17 (32.7)                | 23 (35.9)                | 48 (32.9)    |
| Other                             | 6 (20)        | 16 (30.8)                | 16 (25)                  | 38 (26)      |
| **Smoking, N (%)**                  |               |                          |                          |              |
| Never smoker                       | 25 (83.3)     | 39 (75)                  | 42 (65.6)                | 106 (72.6)   |
| Former smoker                      | 5 (16.7)      | 13 (25)                  | 20 (31.3)                | 38 (26)      |
| Current smoker                     | 0             | 0                        | 2 (100)                  | 2 (1.4)      |
| **Alcohol, N (%)**                  |               |                          |                          |              |
| Never drinker                      | 3 (10)        | 6 (11.5)                 | 15 (23.4)                | 24 (16.4)    |
| Former drinker                     | 0             | 0                        | 1 (1.6)                  | 1 (0.7)      |
| Current drinker                    | 27 (90)       | 46 (88.5)                | 48 (75)                  | 121 (82.9)   |
| **BMI (kg/m²), mean (SD)**         | 27.9 (4.5)    | 27.9 (4.2)               | 29.5 (4.02)              | 28.6 (4.2)   |
| **Hypertension, N (%)**             |               |                          |                          |              |
| Yes                                 | 9 (30)        | 17 (32.7)                | 20 (31.3)                | 46 (31.5)    |
| No                                  | 21 (70)       | 35 (67.3)                | 44 (68.8)                | 100 (68.5)   |
| **Diabetes, N (%)**                 |               |                          |                          |              |
| Yes                                 | 1 (3.3)       | 3 (5.8)                  | 2 (3.1)                  | 6 (4.1)      |
| No                                  | 29 (96.7)     | 49 (94.2)                | 62 (96.9)                | 140 (95.9)   |
| **Position played, N (%)**          |               |                          |                          |              |
| Backs                               | 15 (51.7)     | 31 (60.8)                | 31 (50.8)                | 77 (54.6)    |
| Back 3rd                            | 4 (13.8)      | 15 (24.2)                | 30 (37.5)                | 30 (37.5)    |
| **Midfield**                        | 10 (34.4)     | 14 (22.6)                | 39 (48.8)                | 39 (48.8)    |
| Scrum half                          | 1 (3.4)       | 3 (4.8)                  | 11 (13.8)                | 11(13.8)     |
| Forward                             | 14 (48.3)     | 20 (39.2)                | 30 (49.2)                | 64 (45.4)    |
| Back row                            | 3 (10.3)      | 13 (21)                  | 24 (37.5)                | 24 (37.5)    |
| 2nd row                             | 5 (17.2)      | 9 (14.5)                 | 19 (29.7)                | 19 (29.7)    |
| Front row                           | 6 (20.7)      | 8 (12.9)                 | 21 (32.8)                | 21 (32.8)    |
| **Length of career (years), mean (SD)** | 15.2 (6.2)   | 16.02 (6.0)              | 15.9 (4.6)               | 15.8 (5.4)   |
| MMSE score below 25, N (%)          | 0             | 1 (1.9)                  | 4 (6.3)                  | 5 (3.5)      |
| NART score, median (p25, p75)       | 41.5 (39.5,45)| 42 (37.5, 45)            | 42 (38.45)               | 42 (38, 45)  |

(Continues)
| Study center, N (%) | No concussiona | Low concussiona (1–2) | High concussiona (3+) | All |
|-------------------|----------------|-----------------------|-----------------------|-----|
| London            | 11 (36.7)      | 24 (46.2)             | 31 (48.4)             | 66 (45.2) |
| Manchester        | 3 (10)         | 0                     | 4 (6.3)               | 7 (4.8) |
| Bristol           | 0              | 2 (3.8)               | 5 (7.8)               | 7 (4.8) |
| Home              | 14 (46.7)      | 26 (50)               | 23 (35.9)             | 63 (43.2) |
| Remote            | 2 (6.7)        | 0                     | 1 (1.6)               | 3 (2.1) |

aRugby-related; bestimated as total concussions divided by time in years between first and last on a total of 92 participants with 2 or more concussions occurring at least 1 year apart; con missing value; dsmoking and alcohol categorized into ever/never in the multivariable model; ethree missing values; ffive missing values; gback 3 include wings and full back positions; hmidfield include center and fly half positions; iback rows include number 8 and flanker positions; jfront row include props and hookers; k18 missing values; lthree missing values (remote participants).

Abbreviations: BMI, body mass index; MMSE, Mini-Mental State Examination; NART, National Adult Reading Test; PACC, Preclinical Alzheimer Cognitive Composite; SD, standard deviation.

FIGURE 1 Categories of concussions by length of career in the BRAIN Study (N = 143)

0.26]). However, the β-coefficients for the high concussion category compared to no concussion decreased with increasing age. In the 80+ age group, having had three or more concussions was associated with a decreased cognitive function of about one SD below the mean PACC score (β = −1.04 [95% CI: −1.62, −0.47]). β-coefficients were plotted against age using restricted cubic splines (Figure 3): the association of high concussion and PACC over age showed a steep decline starting from about age 75 years. Length of career was not associated
### TABLE 2
Median (p25, p75) scores for the individual cognitive function tests, by concussion and age categories

|               | N   | PACC score, median (p25, p75) | MMSE, median (p25, p75) | FNAME score, median (p25, p75) | Logical-Memory Delayed Recall, median (p25, p75) | Digit-Symbol Substitution, median (p25, p75) |
|---------------|-----|-------------------------------|-------------------------|---------------------------------|-----------------------------------------------|-----------------------------------------------|
| **All ages**  |     |                               |                         |                                 |                                               |                                               |
| No concussion | 27  | 0.04 (–0.32, 0.34)            | 29 (28, 30)             | 66 (45, 74)*                    | 9 (6, 13)*                                    | 41 (37, 49)                                   |
| Low concussion| 52  | –0.04 (–0.62, 0.43)           | 29 (28, 30)             | 53.5 (34.5, 78)                 | 9 (5.5, 11.5)                                 | 46 (40, 53.5)                                 |
| High concussion| 63  | 0.31 (0.004, 0.70)            | 29 (28, 30)             | 74 (56, 82)                     | 10 (8, 13)                                    | 52.5 (40, 62)*                                |
| **Age 50–59 (N = 28)** |     |                               |                         |                                 |                                               |                                               |
| No concussion | 5   | 0.47 (0.20, 0.64)             | 30 (30, 30)             | 72 (69, 74)                     | 10 (9, 13)                                    | 61 (48, 63)                                   |
| Low concussion| 8   | 0.68 (–0.10, 0.93)            | 30 (30, 30)             | 73 (49.5, 87)                   | 11.5 (8, 15)                                  | 52.5 (44, 61)                                 |
| High concussion| 15  | 0.74 (0.46, 0.91)             | 30 (39, 30)             | 79 (74, 89)                     | 11 (8, 14)                                    | 63 (54, 67)                                   |
| **Age 60–69 (N = 43)** |     |                               |                         |                                 |                                               |                                               |
| No concussion | 5   | 0.18 (0.07, 0.78)             | 29 (29, 29)             | 79 (52, 82)                     | 8 (6, 14)                                     | 49 (49, 65)                                   |
| Low concussion| 13  | 0.33 (–0.05, 0.55)            | 30 (28, 30)             | 68 (49.79)                      | 9 (6, 11)                                     | 51 (45, 55)                                   |
| High concussion| 25  | 0.40 (–0.13, 0.65)            | 30 (29, 30)             | 75 (64, 82)                     | 11 (9, 13)                                    | 55.5 (47, 62)                                 |
| **Age 70–79 (N = 47)** |     |                               |                         |                                 |                                               |                                               |
| No concussion | 8   | –0.04 (–0.32, 0.20)           | 29 (28, 29)             | 67 (45, 75)                     | 12 (9, 13)                                    | 42 (38, 46)                                   |
| Low concussion| 22  | –0.08 (–0.60, 0.21)           | 29 (28, 30)             | 51.5 (41, 69)                   | 8.5 (5, 11)                                   | 45.5 (42, 49)                                 |
| High concussion| 17  | 0.01 (–0.31, 0.27)            | 29 (28, 30)             | 58 (41, 79)                     | 10 (8, 11)                                    | 42 (37, 53)                                   |
| **Age 80–89 (N = 25)** |     |                               |                         |                                 |                                               |                                               |
| No concussion | 10  | –0.44 (–0.88, –0.10)          | 28.5 (28, 29)           | 50 (34, 65)                     | 8.5 (4, 10)                                   | 35 (29, 40)                                   |
| Low concussion| 9   | –0.75 (–1.15, –0.27)          | 29 (28, 30)             | 33 (13, 34)                     | 8 (3, 10)                                     | 28 (28, 38)                                   |
| High concussion| 6   | –2.33 (–2.94, –0.51)          | 23 (20, 28)             | 5.5 (0, 27)                     | 1 (0, 7)                                      | 32 (14, 36)                                   |

*One missing value.

Abbreviations: FNAME, Face–Name Associative Memory Exam; MMSE, Mini-Mental State Examination; PACC, Preclinical Alzheimer Cognitive Composite.

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**FIGURE 2** Preclinical Alzheimer Cognitive Composite (PACC) score distribution by age group in the BRAIN Study (N = 143)
TABLE 3  Linear regression coefficient for the associations between rugby-related concussions and length of playing career and PACC scores, adjusted for potential confounders

|                         | N   | Age-adjusted coefficient (95% CI)a | Fully adjusted coefficient (95% CI)b   |
|-------------------------|-----|-----------------------------------|--------------------------------------|
| No concussion           | 27  | Reference                         | Reference                             |
| Low concussion (1-2)    | 52  | -0.18 (-0.48, 0.12)              | -0.09 (-0.37, 0.19)                  |
| High concussion (3+)    | 63  | -0.08 (-0.38, 0.22)              | -0.03 (-0.31, 0.26)                  |
| Total concussions       |     | -0.01 (-0.04, 0.03)              | -0.0002 (-0.03, 0.03)                |
| Concussion densityc     |     | 0.01 (-0.17, 0.19)               | -0.03 (-0.22, 0.16)                  |
| Length of career, yearsd|     | -0.01 (-0.03, 0.01)              | 0.001 (-0.02, 0.02)                  |

| Age 50–59 (N = 28)      |     |                                   |                                      |
| No concussion           | 5   | Reference                         | Reference                             |
| Low concussion (1-2)    | 8   | 0.03 (-0.64, 0.70)               | 0.19 (-0.44, 0.81)                   |
| High concussion (3+)    | 15  | 0.20 (-0.41, 0.81)               | 0.47 (-0.11, 1.04)                   |
| Total concussions       |     | -0.01 (-0.10, 0.09)              | 0.04 (-0.06, 0.13)                   |
| Concussion density      |     | 0.06 (-0.59, 0.72)               | -0.08 (-0.75, 0.60)                  |
| Length of career, years |     | -0.01 (-0.08, 0.07)              | 0.04 (-0.03, 0.11)                   |

| Age 60–69 (N = 43)      |     |                                   |                                      |
| No concussion           | 5   | Reference                         | Reference                             |
| Low concussion (1-2)    | 13  | -0.12 (-0.74, 0.50)              | -0.37 (-0.94, 0.21)                  |
| High concussion (3+)    | 25  | 0.22 (-0.36, 0.79)               | -0.004 (-0.54, 0.53)                 |
| Total concussions       |     | 0.01 (-0.04, 0.05)               | 0.003 (-0.035, 0.04)                 |
| Concussion density      |     | 0.03 (-0.19, 0.25)               | -0.01 (-0.22, 0.21)                  |
| Length of career, years |     | -0.02 (-0.05, 0.01)              | 0.0 (-0.03, 0.03)                    |

| Age 70–79 (N = 47)      |     |                                   |                                      |
| No concussion           | 8   | Reference                         | Reference                             |
| Low concussion (1-2)    | 22  | -0.26 (-0.76, 0.23)              | 0.01 (-0.46, 0.47)                   |
| High concussion (3+)    | 17  | -0.07 (-0.58, 0.44)              | -0.11 (-0.58, 0.36)                  |
| Total concussions       |     | 0.002 (-0.05, 0.06)              | 0.002 (-0.05, 0.05)                  |
| Concussion density      |     | -0.20 (-0.58, 0.18)              | -0.30 (-0.71, 0.10)                  |
| Length of career, years |     | 0.01 (-0.04, 0.03)               | -0.001 (-0.03, 0.03)                 |

| Age 80–89 (N = 25)      |     |                                   |                                      |
| No concussion           | 10  | Reference                         | Reference                             |
| Low concussion (1-2)    | 9   | -0.23 (-0.77, 0.31)              | -0.15 (-0.66, 0.35)                  |
| High concussion (3+)    | 6   | -1.42 (-2.02, -0.81)             | -1.04 (-1.62, -0.47)                 |
| Total Concussions       |     | -0.32 (-0.47, -0.18)             | -0.24 (-0.38, -0.09)                 |
| Concussion Density      |     | -0.02 (-0.48, 0.44)              | 0.002 (-0.45, 0.46)                  |
| Length of career, years |     | -0.04 (-0.10, 0.01)              | -0.04 (-0.09, 0.01)                  |

Test for interaction with age groups

| Concussion groups (shown above) | P = 0.003 |
| Total concussions               | P = 0.011 |
| Concussion density              | P = 0.590 |
| Length of career, years         | P = 0.220 |

aNcluding imputed values, excluding remote participants, N = 143;
badjusted for: age, highest educational qualification, smoking status, alcohol use, rugby position, NART test, BMI, occupation, medical history (high blood pressure, diabetes), and assessor;
cN = 92.
dN = 126.

Abbreviations: BMI, body mass index; CI, confidence interval; NART, National Adult Reading Test; PACC, Preclinical Alzheimer Cognitive Composite.
with measures of cognitive function, although an interaction with age was detected, and a borderline significant negative association was observed for participants aged 80+ years.

The analyses were repeated using the individual test results (Table S3 in supporting information). Among participants aged 80+ years, having had three or more concussions was associated with a worse performance on the MMSE and the FNAME test compared to participants of the same age who were not exposed to concussion. This association was strongest for the MMSE (β = −2.18 [95% CI: −3.03, −1.34]). Conversely, in the same age group, length of rugby career was associated with worse delay recall at the logical memory (β = −0.08 [95% CI: −0.16, −0.003]).

The findings for total concussion did not change substantially (Table S4 in supporting information); conversely, concussion density was found to be not associated with PACC in any of the analyses. Neither age at first concussion, nor at first rugby-related concussion, was associated with PACC scores (results not shown).

The sensitivity analysis conducted after removing imputed values (Table S5 in supporting information) and after removing study assessor from the model (results not shown) yielded virtually unchanged results. Conversely, removing the five cognitively impaired cases (MMSE < 25/30) yielded overall attenuated coefficients, and there was then no interaction with age (P = 0.43), resulting in a lack of association between concussion and PACC scores even among older participants (β = 0.01 [95% CI: −0.69, 0.71]; Table S6 in supporting information).

4 | DISCUSSION

The findings of the BRAIN Study, conducted among former elite rugby players, suggest that having suffered rugby-related concussions during their playing career, or the length of the rugby career, are not associated with an overall worse long-term cognitive function. However, the relationship changed with age: among older former players (80+ years), having suffered more than three concussions is associated with a decrease in cognitive function of about 1 SD below the mean PACC score compared to former players of the same age who have suffered no concussion. The spline analysis suggested that this increased risk starts from about age 75 years. These findings are consistent with the comparison with non-impaired subjects: the study participants showed better mean scores than predicted in the younger age groups, and worse at older age. However, this effect in the older ages appeared to be driven by a small number of older participants in the high concussion group who were considered cognitively impaired according to their MMSE scores. In the same age group, a longer rugby career was associated with a worse delayed recall; however, its overall effect on PACC score was relatively weak. Further studies are therefore needed to confirm these findings among older individuals.

The main limitation of this study is the cross-sectional design, and potential susceptibility to recall bias. This was minimized by using the BRAIN-Q tool to assess history of concussion. Unfortunately, further external validation using clinical records or video recording was
Length of career may be a proxy measure for cumulative repetitive subconcussive head injury caused by the participation in contact sports, as suggested by the finding of higher level of serum biomarkers associated with oxidative stress and vascular damage among contact sportsmen. Consistently, evidence from other sports strongly suggests an association of length of career with neuropathological findings compatible with CTE (including p-tau pathology, inflammation, and white matter rarefaction), in American footballers or with the onset of clinical dementia, in soccer players. Intriguingly, this last study also observed an increased risk of mortality from neurodegenerative diseases after the age of 80 years compared to population-based controls (after an initial decreased risk of mortality at younger ages). Although these two studies are not directly comparable if the findings are both correct, then any effects of sports-related concussion and/or subconcussive repeated head injury on mortality from neurodegenerative disease is unlikely to be mediated through mechanisms that result in impaired cognitive function at earlier ages.

These findings are also consistent with a life-course approach to dementia, our sample included highly educated and professionally engaged people; thus, it is plausible that their cognitive reserve would compensate for cognitive function impairment until a higher-than-normal threshold is reached. Moreover, the higher-than-average social status and the overall healthy habits may confer an additional protective/delaying effect on the onset of the cognitive impairment, which may manifest itself at a later-than-expected age. This may explain why these data are not directly consistent with findings from other sports, or from less selected populations.

Some caution is needed before generalizing these results to other populations and time periods. A large part of the present sample included participants with a degree from Universities of Oxford/Cambridge, whereas rugby players may have different demographic profiles in other countries. Moreover, the game has changed considerably in the last 30 years, becoming faster with more contact events with a greater propensity to cause concussion, ball-in-play time has increased, and there have been increases in the weight of all players and the height of backs. Over time, the identification and management of concussion will have also significantly improved.

5 | CONCLUSIONS

This study found no overall evidence of an association between rugby-related concussion and cognitive function, but there was an increased risk in older adults aged 75+ years who reported three or more concussions (compared to none).

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CONFLICTS OF INTEREST
We declare that we have no conflicts of interest. Support received for the present work: The Drake Foundation supported this study with a grant awarded to the London School of Hygiene and Tropical Medicine to NP, VG, and DM. GS, SM, CH, and LJ were paid off the grant. All co-authors are co-investigators of the BRAIN Study. SK is employed by the Rugby Football Union as their Medical Services Director; SM and CH were paid out of the research grant; MD received also funds from the Rugby Football Union, and the Centre for Sport, Exercise and Osteoarthritis Versus Arthritis. Support received outside the submitted work: VG, NP, and DM received another grant from the Drake Foundation (2018-2020) awarded to the London School of Hygiene and Tropical Medicine. VG received grants from Barts and The London Charity (2019-2020), UKRI-GCRF MRC-CONCYTEC (2019-2022), and the London International Development Centre (2018-19) all through her institution. DM received grants from the Brazilian Steel Institute, Kingspan Health and Safety Executive Aarhus University Hospital, Emirates Global Aluminium Guys, and St Thomas’ University Hospital, through his institution. EW received grants from MRC and NIHR, both unrelated to present work and through her institution. MD received support from the British Medical Association, the Rugby Football Union, the Rugby Football Union’s Injured Players Foundation, and the British Horseracing Association, all through her institution. AM received grants from Barts Charity (2021 – 20250): Integrative bioinformatics analysis of fluid-tissue proteomics to develop an ALS predictive model for biomarkers and therapeutic targets discovery. £184,194.40 (2019 – 2023) Barts and the London Charity, UCB Pharma SPRL. NIH (2018-2022) Immune reactivity to neurofilaments: therapeutics and biomarkers for ALS. £ 133,769. NIH (2022) Pre-Symptomatic ALS Prelude to a Disease Prevention Trial. NIH- 95258, $ 215, 851 2018. NIH Clinical trial readiness in ALS National Institutes of Health – USA, NIH-U01 Multi-PI grant award. $ 367,372. All payments have been made to his institution. KS received money from Rugby Football Union, England Rugby Injury and Training Audit (2019-2023); Rugby Football Union, Community Rugby Injury Surveillance Project (2017-21); Community, Schools and Universities, (2017-2021) Arthritis Research UK, ARUK Centre Renewal (2018-2023); RFU Injured Players Foundation, Spinal Cord Injury Surveillance in Rugby, (2012-2021); The Racing Foundation, Analysis of Spinal Injuries in Horseracing, (2020-2023); British Horseracing Authority, Covid-19 Surveillance in Racing, (2020-2021); World Rugby, The contribution of in-game fatigue and use of replacements to injury risk in professional rugby union, (2020-2021). 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HZ has served at scientific advisory boards and/or as a consultant for Alec-tor, Eisai, Denali, Roche Diagnostics, Wave, Samumed, Siemens Health-ineers, Pinteon Therapeutics, Nervgen, AZTherapies, CogRx and Red Abbey Labs. Payments made to himself. NP received grants for other research, all unrelated to this paper. In addition, NA received consultancy fees from Pfizer/Lilly 2018; Bristows LLP 2019; and Novartis 2021 with payments directed to himself. AM received consultancy fee from Cross-molecule Advisory Board in Neurofilaments (NFL), and Hoffmann-La Roche Ltd with payment made to himself. SC has received consultancy fees from the Wellcome Trust, payment to himself. HZ has served at scientific advisory boards and/or as a consultant for Alector, Eisai, Denali, Roche Diagnostics, Wave, Samused, Siemens Healthineers, Pinteon Therapeutics, Nervgen, AZTherapies, CogRx and Red Abbey Labs. Payments made to himself. NP received grants for other research, all unrelated to this paper. In addition, NA received consultancy fees from Pfizer/Lilly 2018; Bristows LLP 2019; and Novartis 2021 with payments directed to himself. AM received consultancy fee from Cross-molecule Advisory Board in Neurofilaments (NFL), and Hoffmann-La Roche Ltd with payment made to himself. SC has received consultancy fees from the Wellcome Trust, payment to himself. HZ has served at scientific advisory boards and/or as a consultant for Alector, Eisai, Denali, Roche Diagnostics, Wave, Samused, Siemens Healthineers, Pinteon Therapeutics, Nervgen, AZTherapies, CogRx, and Red Abbey Labs. Payments made to HZ. EW received payment for providing training to AstraZeneca, unrelated to current work. AM received payment from Pfizer: for “Disease progression in ALS: cell senescence and metabolism in the driving seat,” lecture. SC received a Siriraj International Visiting Scholar at the Division of Neurology, Department of Medicine, Bangkok, Thailand to himself. 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provided for both claimants and defendants. All payments were to his institution. AM patented with Prof. M. Benatar “Determining onset of amyotrophic lateral sclerosis.” Patent number: B75649EPD40021. SK participated in WADA TUE Expert Group (Honorary) UKAD Innovation and Research Group (Honorary) FA Expert Concussion Panel (Honorary) FIFA Expert Concussion Panel (Honorary) World Rugby Concussion Working Group (Honorary) Chair Ineos Cycling Medical Advisory Group (Paid Personally). Finally, VG is member of the Ethical Committee at Campus Fryslân, since April 2020; member of the Selection Committee of the Young Academy Groningen–University of Groningen, since 2021, editor of Journal of Neurology since January 2020, member of the Industrial Injury Advisory Committee from November 1st 2018 to January 2020 (for this last role, she received personal compensation). HZ is a chair of the Alzheimer’s Association Global Biomarker Standardization Consortium and the AA Biofluid-Based Biomarker PIA. No payments made. HZ is a co-founder of Brain Biomarker Solutions in Gothenburg AB (BBS), which is a part of the GU Ventures Incubator Program. Payments made to HZ. CH received a PhD studentship funded by the GW4 Medical Research Council BioMedical Doctoral Training Partnership at the University of Bath; her Research Associate position at the University of Bristol is funded by the Elizabeth Blackwell Institute for Healthcare Research and Rosetrees Trust. KL and MC have nothing to disclose and report no conflicts of interest.

AUTHOR CONTRIBUTIONS
Study concept and design: V. Gallo, N. Pearce, D. McElvenny; analysis and interpretation of data: G. Seghezzo, E. Williamson, V. Gallo, N. Pearce, K. Lu, D. McElvenny, S. Crutch, S. Kemp; drafting of the manuscript: V. Gallo; data collection: S. Mian, C. Hobbs, D. Davoren, L. James, M. Davies, K. Stokes, M. Cross; critical revision of the manuscript for important intellectual content: D. McElvenny, S. Kemp, E. Williamson, K. Lu, N. Arden, A. Malaspina, M. Loosemore, K. Stoke, M. Cross, S. Crutch, H. Zetterberg, N. Pearce.

DATA AVAILABILITY STATEMENT
Dr Gallo, Ms Seghezzo, Dr Williamson, and Prof Pearce had full access to all of the data in the study and take responsibility for the integrity of the data and the accuracy of the data analysis. Dr Gallo declares that this manuscript is an honest, accurate, and transparent account of the study being reported; that no important aspects of the study have been omitted. All co-authors had full access to the data, and can take responsibility for the integrity of the data and the accuracy of the data analysis.

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SUPPORTING INFORMATION
Additional supporting information may be found in the online version of the article at the publisher’s website.

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