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Neurocognitive performance and mental health of retired female football players compared to non-contact sport athletes

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ABSTRACT

Background Adverse long-term effects of playing football due to repetitive head impact exposure on neurocognition and mental health are controversial. To date, no studies have evaluated such effects in women.

Aims To (1) compare neurocognitive performance, cognitive symptoms and mental health in retired elite female football players (FB) with retired elite female non-contact sport athletes (CON), and to (2) assess whether findings are related to history of concussion and/or heading exposure in FB.

Methods Neurocognitive performance, mental health and cognitive symptoms were assessed using computerised tests (CNS-vital signs), paper pen tests (Category fluency, Trail-Making Test, Digit Span, Paced Auditory Serial Addition Test), questionnaires (Hospital Anxiety and Depression Scale, SF-36v2 Health Survey) and a symptom checklist. Heading exposure and concussion history were self-reported in an online survey and in a clinical interview, respectively. Linear regression was used to analyse the effect of football, concussion and heading exposure on outcomes adjusted for confounders.

Results FB (n=66) performed similar to CON (n=45) on neurocognitive tests, except for significantly lower scores on verbal memory (mean difference (MD)=−7.038, 95% CI −12.98 to −0.08, p=0.038) and verbal fluency tests (MD=−7.534, 95% CI −13.75 to −0.46, p=0.016). Among FB weaker verbal fluency performance was significantly associated with ≥2 concussions (MD=−10.36, 95% CI −18.48 to −2.83, p=0.017), and weaker verbal memory performance with frequent heading (MD=−9.166, 95% CI −17.59 to −0.123, p=0.041). The depression score differed significantly between study populations, and was significantly associated with frequent heading but not with history of concussion in FB.

Conclusion Further studies should investigate the clinical relevance of our findings and whether the observed associations point to a causal link between repetitive head impacts and verbal memory/fluency or mental health.

What are the new findings?

- ► Neurocognitive performance was similar in retired elite female football players and athletes from non-contact sports, except for significantly lower verbal memory and fluency scores.
- ► Reported mental health scores and cognitive symptom prevalences were similar in retired elite female football players and athletes from non-contact sports, except for a significantly worse depression score and a higher prevalence of subjective memory problems.
- ► A history of ≥2 concussions was associated with significantly lower verbal fluency scores among football players.
- ► Higher heading exposure was associated with significantly higher psychomotor speed, but significantly lower verbal memory and worse mental health scores.

INTRODUCTION

The notion that repetitive neurotrauma through sport may lead to chronic brain damage is almost a century old and originated with the description of the 'punch drunk' syndrome (dementia pugilistica) in professional boxers.[1] A renewed interest in the topic, fuelled yet again by several case-studies,[2 3] has led to unprecedented media attention and a significant amount of research in American football players over the past decade.[4 5] There is an increasing although still limited amount of research investigating the long-term effects of concussion and repetitive subconcussive head impacts (RSHI) in retired athletes from other sports, such as rugby,[6–8] ice hockey[9–11] and football (soccer).[12–15]

Given its popularity worldwide and the unique feature of heading, football is of particular interest. It has been proposed that exposure to RSHI in football (ie, heading) may lead to neuronal damage comparable to that of multiple concussions.[16 17] However, two recent meta-analyses on the topic found that a majority of studies did not report a significant relation between heading frequency and adverse outcomes.[18 19] Interestingly, both meta-analyses noted that sample age may have moderated study results: studies involving more senior participants with more extensive lifetime heading exposure were more likely to report adverse outcomes.[18 19] Thus, while several studies with younger players suggested no overall relation between heading and neurocognitive deficits,[20 21] it remains controversial whether such deficits may eventually arise in more senior or retired players.[13]

To date, only six studies with four different samples were conducted in *retired* football players and reported inconsistent results.[12–14 22–24] Two studies reported associations between RSHI and neuroimaging abnormalities,[13 22] while another found an increased risk for amyotrophic lateral sclerosis (ALS) among football players.[12] In contrast, compared with general population values, Vann Jones *et al*[14] found no increased prevalence of mild cognitive impairment (MCI) or dementia among retired male football players and Feddermann-Demont *et al*[25] reported no increased prevalence of playing contact sport or previous head injury among patients with ALS. Turning to studies in deceased players, seven cases of suspected chronic traumatic encephalopathy have been reported in the literature to date.[26] Additionally, deceased football players were found to a have a higher mortality from neurodegenerative diseases than matched controls in a large recent death record study.[15] However, results of the described studies need to be interpreted carefully due to several methodological limitations; these include very small sample sizes or very few observed cases, inappropriate control groups, selection bias and recall bias owing to retrospective research designs.[19]

Next to the described methodological difficulties of studies assessing the late consequences of concussion and RSHI in retired athletes, the research field is currently lacking diversity in the studied populations. To the authors' knowledge, all research to date has been conducted with retired male athletes or outcomes have not been stratified by sex.[27–29] This is an important gap in the literature as there are definite sex differences, for instance in the structure and function of the brain,[30] that may well lead to differential outcomes after concussion. Several reviews[31–33] and studies with active female athletes[34–38] support this notion, and suggest that women may be more vulnerable to the (short to medium term) effects of concussion and RSHI (for exception see Brooks *et al*).[39 40] However, studies on sex differences for longer-term outcomes are less consistent in both sport[41] and non-sport-related[42 43] contexts.

Therefore, the primary aim of this study was to compare neurocognitive performance, cognitive symptoms and mental health of retired elite female football players compared with an age and sex matched control group of retired elite non-contact sport athletes. The secondary aim was to investigate the association of neurocognitive performance, cognitive symptoms and mental health with (1) history of concussion and (2) heading exposure in retired elite female football players.

METHODS

This quantitative, case-control study compared retired elite female football players with age, sex and level of competition matched non-contact sport controls. A particular focus in our choice of control group was to account for the positive effects of elite level exposure to exercise on cognitive function,[44] as possible adverse effects of playing football may be masked when choosing a control group from the general population. We included female football players and non-contact sport controls who had retired from elite sport at least 2 years ago and were aged between 30 and 50 years. Football players were defined as elite, if they had played in the first German or Dutch league and/or for the national team after 1 January 2000. We chose this time frame/age range because it provided us a more homogenous population in relation to training volume and intensity as well as hormonal status. Controls from non-contact sports were considered elite, if they had competed at German or Dutch national championships or for the national team. Participants were excluded if they had a severe (as diagnosed by a physician) non-sport-related head injury or symptomatic disease affecting the central nervous system. Further, control participants who reported more than one previous concussion or any severe head injury were excluded, to minimise the potential effects on the outcome parameter. Individual test results (n=4, 0.5%) were excluded if at least two of the following three indicators deemed the score invalid: (1) the manufacturers validity indicator,[45] (2) the test administrator at time of testing and (3) scores were outliers.

After providing informed consent, the participating athletes completed an online survey, a semistructured interview and a neuropsychological test battery. Testing was carried out in the participants' native language (German, n=80; Dutch, n=31). Demographic and sport-related *participant characteristics* were assessed via an online survey (table 2). Information on *history of concussion* and other head, neck and face injuries (from here onwards referred to as 'other head injuries') was gathered in a semistructured interview, and included diagnosis, year, context, mechanism, symptoms, treatment and severity (time-loss) of injury. Concussion was defined as a direct blow to the head, face, neck or elsewhere on the body with an impulsive force transmitted to the head resulting in specific clinical symptoms that may or may not include loss of consciousness as described by the Concussion in Sports Group.[46] Head injuries during childhood (≤10 years) were not recorded. *Heading* frequency was self-reported and assessed via a single survey item, asking players whether they were rare, moderate and frequent headers.

Neurocognitive performance was evaluated using the computerised test battery CNS vital signs (CNSVS)[47] and four paper pen tests. All tests were chosen due to their sensitivity to subtle cognitive deficits,[48] and specificity in detecting concussion-related impairments.[49 50] The core CNSVS test battery is comprised of seven well-established

Table 1 Description and calculation of domain scores for CNS vital signs

Clinical domain	Test	Domain score calculation	Domain description
Psychomotor speed	FTT, SDC	FTT total taps average +SDC correct responses	Ability to perceive, attend and respond to complex visual–perceptual information and perform simple fine motor tasks.
Reaction time	ST	(ST complex reaction time correct+ST reaction time correct)/2	Speed of reaction to a simple and increasingly complex set of directions.
Complex attention	CPT, SAT, ST	ST commission errors+SAT errors+CPT errors	Ability to track and respond to a variety of stimuli over lengthy periods of time and/or perform complex mental tasks requiring vigilance quickly and accurately.
Cognitive flexibility	SAT, ST	SAT correct responses−SAT errors−ST commission errors	Ability to adapt to a rapidly changing and increasingly complex set of directions and/or to manipulate the information.
Processing speed	SDC	SDC correct responses−SDC errors	Ability to recognise and process information, that is, perceiving/ responding to incoming information, motor speed, fine motor coordination, visual–perceptual ability.
Verbal memory	VBM	Correct hits and passes immediate+correct hits and passes delay	Ability to remember (recognise and retrieve) words.
Visual memory	VIM	Correct hits and passes immediate+correct hits and passes delay	Ability to remember (recognise and retrieve) geometric figures.

CPT, Continuous Performance Test; FTT, Finger Tapping Test; SAT, Shifting Attention Test; SDC, Symbol Digit Coding Test; ST, Stroop Test; VBM, Verbal Memory Test; VMT, Visual Memory Test.

neuropsychological tests, which generate 11 domain scores. Seven domain scores were included in the analysis (table 1). Excluded domain scores were either considered redundant or were lacking variability (ie, 100% of participants scored ≥39 of 40 points on the continuous performance test). The pen and paper test battery included the Category Fluency Test (CFT), the Digit Span Test (DST) the Trail-Making Test (TMT) and the Paced Auditory Serial Addition Test (PASAT). Scores analysed in this study were: CFT: category: animals, time: 1 min; DST: sum of total correct answers in forward and backward condition; TMT: time A and time B; PASAT: sum of total correct answers (max. 59/trial) in trials one (2.4 s), two (2.0 s) and three (1.8 s). For ease of interpretation, all raw scores were standardised and inverted where necessary, resulting in a uniform scale with a mean of 100, an SD of 15 and higher scores reflecting better performance.

Cognitive symptoms typically observed in concussion patients with persistent symptoms were assessed via six items (dizziness, concentration and memory problems, fatigue, sleep disturbance, mood instability) on a scale from 0=no problem to 3=severe problem during the last 3 months. For analysis, a summary score was calculated (range: 0–18), and in addition each symptom was dichotomised (1=minor to severe problem or 0=no problem) for exploratory item-level analysis.

Mental health was assessed using the German and Dutch versions of the Hospital Anxiety and Depression Scale (HADS)[51] and the mental health subscale of the SF-36v2 Health Survey (SF-36).[52]

Statistical analysis

All data were processed with SPSS (V.25, IBM). Descriptive statistics are presented as means with SDs or median with IQR for continuous variables and frequencies with percentage for categorial variables. To investigate (1) differences in neurocognitive performance, mental health and cognitive symptoms between football players and non-contact sport controls we used linear regression analysis adjusted for the control variables. To assess (2) the effect of history of concussion (multiple:≥2, single:1, none:0) and heading exposure (frequent, moderate, rare) on neurocognitive performance, mental health and cognitive symptoms, we also used linear regression analysis (adjusted for the control variables), comparing both exposure groups to the no exposure group. Exploratory item-level analysis of cognitive symptoms was carried out descriptively using frequencies with percentage for all research questions.

Analyses of neurocognitive performance were adjusted for age, years of education, bodily pain (SF-36) and depression symptoms (HADS), while analyses of mental health and cognitive symptoms were adjusted for age and bodily pain only. Next to the sociodemographic characteristics associated with the described outcomes we included bodily pain to ensure that differences in injury profiles and subsequent long-term consequences between contact and non-contact athletes don't confound the results.[53] Further, depression may influence cognitive performance, and thus, was included as a control variable.[54] Analyses using heading exposure as the grouping variable were additionally adjusted for history of concussion.[18]

Parameter estimates of the linear regression analysis were reported with 95% bias corrected and accelerated CIs and respective p values based on 1000 bootstrap samples, due to violation of assumptions related to normality and/or homoscedasticity. Alpha was set at $p<0.05$.

Patient and public involvement

We did not directly include PPI in this study, but the study design and participant relevant outcomes were developed in collaboration with a participant representative. Participants were not invited to contribute to the writing or editing of this document for readability or accuracy.

RESULTS

Study population

Of the 144 volunteers who registered for the study, 18 were excluded due to reporting a severe non-sport related concussion (n=2) or not meeting the inclusion criteria for age (n=12), gender (n=2), elite sport (n=1) or length of retirement (n=1). Fifteen volunteers were not available during the study period or stopped responding. Finally, 111 participants were included in the study: 66 football players and 45 controls from 17 different non-contact team and individual sports (eg, volleyball and rowing). Demographic and sport-related characteristics by study population are presented in table 2. Study populations were similar with the exception of training load and education.

Head injuries

In total, 71 concussions and 47 other head injuries (includes neck and face) were reported (table 2). Diagnosis was made by a physician in 76.1% of concussions and 68.1% of other head injuries. Other head (and neck) injuries included fractures, various cervical spine injuries, contusions, lacerations and tooth injuries. Most concussions (90.0%) and other head injuries (77.1%) were sport related. Median time loss was 7 days (IQR=11.5) for concussions and 2 days (IQR=9.3) for other head injuries. Loss of consciousness was reported in 7.1% of concussions. Time since the most recent concussion ranged between 1 year and 32 years, with a median of 15 years (IQR=8.0). Among football players, 50.0% (n=33) reported no history of concussion, 30.3% (n=20) had a single concussion and 19.7% (n=13) had multiple (range=2–11) concussions. Further, 56.1% (n=37) reported no other head injuries, 33.3% (n=22) had a single other head injury and 10.6% (n=7) multiple (≥2) other head injuries. Among control athletes, both concussions (n=2, 4.4%) and other head injuries (n=6, 13.3%) were rare and no control athlete had multiple head injuries.

Table 2 Characteristics of retired female elite athletes by study population

Sample (n=111)	Football (n=66)	Non-contact sport (n=45)
Age, mean (SD)	37.4 (4.8)	35.8 (5.4)
Nationality German, n (%)	51 (77.3)	29 (64.6)
Handedness right, n (%)	61 (92.4)	39 (86.7)
Education in years, mean (SD)	17.3 (2.7)	18.3 (1.9)
No regular physical activity, n (%)	12 (18.2)	8 (17.8)
Bodily pain on SF-36, mean (SD)[a]	77.9 (23.1)	83.8 (19.8)
Retired since in years, mean (SD)	8.6 (4.4)	9.8 (4.7)
Career length in years, mean (SD)	11.0 (4.8)	11.9 (5.6)
Training sessions per week, mean (SD)	5.0 (1.4)	8.5 (3.8)
Matches/competitions per year n (%)		
≥45	10 (15.2)	3 (6.7)
25–44	28 (42.2)	16 (35.6)
≤24	28 (42.2)	26 (57.8)
Concussion, mean (SD)	1.05 (1.82)	0.04 (0.03)
Other head injury, mean (SD)	0.62 (0.11)	0.13 (0.05)
Heading, n (%)		
Frequent	24 (36.4)	n/a
Moderate	31 (47.0)	
Rare	11 (16.7)	
Playing position, n (%)		
Defender	22 (33.3)	n/a
Midfielder	26 (39.4)	
Attacker	11 (16.7)	
Goalkeeper	7 (10.6)	

*Higher scores=less bodily pain.
SF-36, SF-36v2 Health Survey.

Football players compared with non-contact sport controls

Football players generally performed better than control athletes on *neurocognitive tests* related to attention and cognitive flexibility, while the opposite was the case for tests of memory and verbal ability (table 3). Similar performance was observed on tests of (information) processing speed. Statistically significant differences between study populations were only found on test of verbal memory (figure 1) and category fluency with football players performing weaker than controls (table 3).

Football players reported similar global *mental health* and anxiety scores compared with controls, but statistically worse depression and *cognitive symptoms* sum scores (table 3). Item-level analysis revealed that the observed

Table 3 Estimated effect of playing football on neurocognitive performance, cognitive symptoms and mental health

	MD†	95% CI‡	P value‡
Computerised tests§			
Psychomotor speed	1.258	–4.81 to 7.50	0.672
Reaction time	0.607	–5.72 to 7.25	0.847
Complex attention	6.043	–0.78 to 12.38	0.062
Cognitive flexibility	3.782	–2.82 to 10.44	0.212
Processing speed	–0.437	–7.14 to 6.85	0.906
Verbal memory	–7.038	-12.98,–0.08	0.038*
Visual memory	–4.757	–10.27 to 1.78	0.127
Pen and paper tests§			
Category fluency	–7.534	-13.75,–0.46	0.016*
Digit span	–1.661	–7.79 to 4.21	0.580
TMT A	0.472	–4.97 to 6.15	0.876
TMT B	–2.331	–7.95 to 2.93	0.385
PASAT	4.955	–0.32 to 10.13	0.082
Cognitive symptoms¶			
Sum score**	1.050	0.03 to 1.98	0.044*
Mental health¶			
HADS depression**	0.969	0.20 to 1.71	0.026*
HADS anxiety**	0.090	–0.90 to 1.06	0.861
SF36 mental health	–1.988	–6.02 to 2.11	0.336

**P<0.05.
†Control group as reference.
‡Bias corrected and accelerated based on 1000 bootstrap samples.
§Adjusted for age, education, bodily pain, depression.
¶Adjusted for age, bodily pain.
**Lower scores=better functioning
HADS, Hospital Anxiety and Depression Scale; MD, mean difference; PASAT, Paced Auditory Serial Addition Test; SF-36, SF-36v2 Health Survey; TMT, Trail-Making Test.

difference in cognitive symptoms sum score was mainly due to a higher prevalence of memory problems in football players (63.6%) than in controls (40.0%; figure 2).

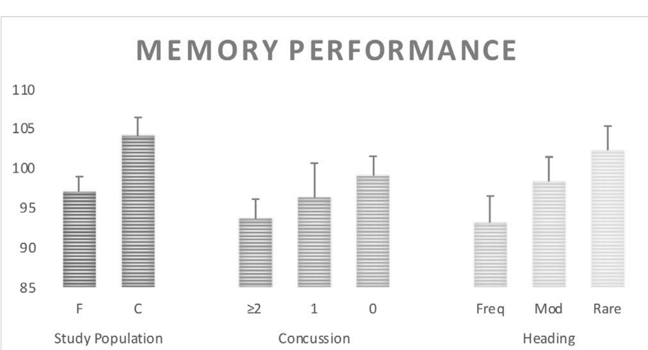

Figure 1 Verbal memory scores by research question. Note: F, football players; C, control athletes; Freq, frequent; Mod, moderate; Error bars=SE error.

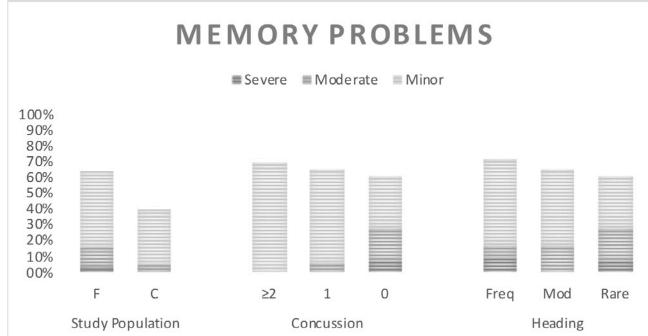

Figure 2 Prevalence of minor to severe memory problems in the last 3 months by research question. Note: F, football Players; C, control athletes; Freq, frequent; Mod, moderate.

The effect of history of concussion in football players

While a history of a single previous concussion did not show a consistent effect on *neurocognitive performance*, having incurred multiple concussions showed weaker neurocognitive performance on almost all tests (figure 3). However, differences were small, with the exception of effects observed on tests related to verbal memory/verbal ability and psychomotor speed (figures 1 and 3). Statistically only category fluency performance was significantly different across concussion groups. Players with a history of multiple concussions had significantly decreased category fluency scores compared with players with no history of concussion (MD=–10.36, 95% CI –18.48 to –2.83, p=0.017), while players with a single previous concussion did not (MD=0.93, 95% CI –5.83 to 7.43, p=0.804).

Cognitive symptoms and *mental health* were similar across concussion groups, and no statistically significant differences were found. Further, item-level analysis of cognitive symptoms showed no relevant, consistent differences between concussion groups.

THE EFFECT OF HEADING EXPOSURE IN FOOTBALL PLAYERS

Overall heading exposure did not show a consistent effect on *neurocognitive performance* (table 4). However, there was a significant difference between heading groups on tests of psychomotor speed and verbal memory (table 4).

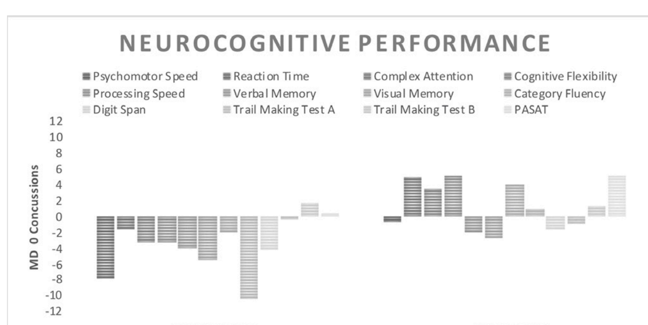

Figure 3 Mean difference (MD) in neurocognitive performance between players with and without a history of concussion (reference group). Note: MD, mean difference; PASAT, Paced Auditory Serial Addition Test.

Table 4 Estimated effect of heading exposure on neurocognitive performance, mental health and cognitive symptoms

	Frequent versus rare			Moderate versus rare		
	MD†	95% CI‡	P value‡	MD†	95% CI‡	P value‡
Computerised tests§						
Psychomotor speed	13.768	−2.06 to 30.11	0.086	16.027	1.97 to 31.83	0.041*
Reaction time	−4.374	−15.66 to 5.85	0.431	−1.366	−11.74 to 8.70	0.770
Complex attention	7.607	−2.87 to 18.68	0.157	−0.848	−10.60 to 12.49	0.878
Cognitive flexibility	3.156	−7.83 to 15.93	0.581	−0.818	−12.37 to 13.76	0.914
Processing speed	4.073	−8.37 to 17.84	0.518	6.572	−5.93 to 18.75	0.253
Verbal memory	−9.166	−17.59 to −0.12	0.041*	−3.935	−12.86 to 5.72	0.388
Visual memory	−4.368	−16.66 to 7.84	0.486	−8.435	−21.17 to 4.77	0.197
Pen and paper tests§						
Category fluency	0.184	−9.15 to 10.52	0.975	1.662	−9.39 to 13.62	0.770
Digit span	−4.509	−15.98 to 9.43	0.479	−9.247	−22.99 to 3.84	0.124
TMT A	−4.571	−18.12 to 11.56	0.487	−1.824	−12.83 to 10.48	0.750
TMT B	−2.798	−14.92 to 9.63	0.675	−5.304	−16.07 to 7.61	0.356
PASAT	−5.909	−17.13 to 5.11	0.288	−1.946	−13.30 to 9.58	0.741
Cognitive symptoms¶						
Sum score**	1.372	−0.51 to 2.95	0.198	0.432	−1.30 to 1.87	0.631
Mental health¶						
HADS depression**	1.516	0.11 to 2.92	0.050*	0.203	−0.91 to 1.41	0.746
HADS anxiety**	2.179	0.29 to 3.83	0.030*	1.089	−0.62 to 2.64	0.219
SF36 mental health	−13.203	−19.69 to −6.72	0.001*	−7.286	−14.26 to −0.62	0.028*

*P<0.05.
†Control group as reference.
‡Bias corrected and accelerated based on 1000 bootstrap samples.
§Adjusted for age, education, bodily pain, depression.
¶Adjusted for age, bodily pain.
**Lower scores=better functioning.
HADS, Hospital Anxiety and Depression Scale; MD, mean difference; PASAT, Paced Auditory Serial Addition Test; SF36, SF-36v2 Health Survey; TMT, Trail-Making Test.

Both frequent and moderate headers had higher psychomotor speed scores than rare headers, but only the difference between moderate and rare headers was statistically significant (table 4). In contrast, frequent heading exposure showed lower verbal memory scores than rare headers (table 4, figure 1).

Cognitive symptom sum score and *mental health* outcomes were worse with increasing heading exposure. The observed differences were statistically significant between frequent and rare headers for all three mental health measures, and between moderate and rare headers for the global mental health scale (table 4). Item-level analysis of *cognitive symptoms* showed no relevant, consistent differences between heading groups with the exception of a noteworthy trend in prevalence of memory problems (frequent=70.8%, moderate=64.5%, rare=45.5%; figure 2).

DISCUSSION

The primary aim of the study was to compare neurocognitive performance, cognitive symptoms and mental health in retired elite female football players with retired elite female non-contact sport athletes.

Neurocognitive performance and cognitive symptoms

We found that neurocognitive performance of female football players and controls was similar on most tests, with exception of the verbal memory and fluency tests. Female football players showed significantly lower performance on tests related to verbal memory and fluency compared with non-contact sport controls 9 years (on average) after retiring from elite sport. Interestingly, visual memory performance was statistically not significantly different between study groups (MD=4.8; 95% CI −10.27 to 1.78). Subgroup analysis among football players suggested that the results related to verbal memory and fluency outcomes may be associated with a history of multiple concussions and frequent heading. A significant associations between repetitive head impacts and visual memory has also been reported from a prospective study in active female football players.[55] A pathophysiological explanation for this association may be that areas related to learning/memory, such as the medial temporal lobes were identified as brain regions experiencing peak strain during head impacts in contact sport athletes.[56] The observed differences on objective measures of verbal memory performance were corroborated by similar data trends in prevalences of self-reported memory problems (figures 1 and 2). However, while the prevalence of subjective memory problems among retired football players was high (63.6%), average verbal memory scores on objective measures were in line with values reported in the general population.[47] Further, based on general population norms, only 10% and 2% of football players had verbal memory scores indicating possible (<25th percentile) or probable (<9th percentile) impairment, respectively. Thus, the clinical relevance of the observed differences is questionable.

Findings from previous literature evaluating memory performance, subjective memory problems or MCI/dementia prevalences in retired/deceased athletes are mixed. While some authors reported a significant association between adverse outcomes and contact sport exposure or a history of concussion,[6 13 15 57–60] others did not,[8 14 32 61 62] and some reported inconclusive results.[29 63 64] Yet, comparability of these studies with the present analysis may be limited, as they were all conducted in male athletes. To the authors knowledge there is no research on this topic in retired female athletes; however, there is limited evidence on the effect of repetitive, mostly mild, traumatic brain injuries in women subjected to intimate-partner violence.[65–67] Similar to our results, the authors found moderate correlations across studies between measures of learning/memory and brain injury scores (based on frequency and recency). Additionally, learning/memory performance and brain injury scores were associated with abnormalities on neuroimaging.[65 67] Thus, while the results of the present investigation are intriguing and in line with the limited previous research, longitudinal studies are necessary to assess whether there is a causal relationship between repetitive concussion/RSHI and verbal memory decline, as other factors not accounted for in this retrospective study may explain the observed group differences.

Is there a cumulative effect of multiple concussions?

Another noteworthy finding of this study is that reporting one previous concussion did not show an effect on neurocognitive performance, while having incurred multiple concussions (ie, ≥2) was consistently associated with lower scores in almost all tests (figure 3). However, these differences did not reach statistical significance for most variables, likely due to small sample sizes in the subgroups and the corresponding lack of power. In a meta-analysis comparing active athletes with one and multiple previous concussions, no overall effect on neurocognitive performance was found; however, follow-up analysis revealed domain specific effects on delayed memory and executive functioning.[68] In studies with retired male contact sport athletes number of concussions was generally not related to inferior neurocognitive outcomes.[6 10 29 69] As there are no studies investigating the cumulative long-term effect of multiple concussions in adult female athletes, more research is clearly needed.

The association of heading and neurocognitive performance

With regard to the long-term effect of heading in retired female players, there were no consistent findings in relation to lower neurocognitive test performance. The verbal memory domain showed a similar performance trend as noted in relation to concussion (after adjusting for history of concussion), which could be an interesting avenue for future research. In contrast, the psychomotor speed domain showed a significant positive association with heading frequency; both moderate and frequent headers outperformed rare headers. We hypothesise that the specific skill of heading or playing positions may require superior psychomotor speed abilities. The results are in line with findings from research on the short-term effects of heading, with a majority of studies reporting no significant association between heading exposure and adverse neurocogntive outcomes.[18 19] In retired male players, evidence is mixed and limited[13 14 22]; however, the largest investigation including 92 players aged 67 years on average also reported no difference in performance on an MCI screening tool between rare headers (goal keepers) and frequent headers (field players).[14] Similarly, Mackay *et al*[15] found no significant difference in mortality from neurodegenerative disease between goalkeepers and field players; however, dementia-related medications were prescribed less frequently to goalkeepers.

Mental health outcomes

We found no significant differences between study populations with regard to anxiety or the global mental health. However, in line with a recent study in retired male rugby players, the depression score was significantly higher in football players than in controls.[70] Yet, the clinical relevance of these findings is questionable, as average depression scores in both study populations (football: 2.7; control: 1.7) were lower than normative values reported in the general German population (3.9–4.5)[71] and far lower than the published clinical cut-off values (≥8/11).[51] According to these cut-off values, only 4.5% of football players and none of the controls had a probable depression; the corresponding prevalence reported in the general German population is 12.8%.[71] Further, in contrast with a recent review,[72] we found no support for an association between concussion history and depression symptoms. However, there were significant associations of heading frequency with depression, anxiety and global mental health.

Limitations

While our study was carefully designed, it has several limitations, which need to be considered when interpreting the results. Power in subgroup analyses was low due to insufficient sample size. Heading exposure was retrospectively assessed by self-report, and might be affect by recall bias. Therefore, we may not have been able to detect potentially meaningful differences related to concussion history or heading exposure. On the other hand, spurious results are possible, as insufficient sample size prevented us from correcting for type 1 error. However, our main findings were consistent across modalities, which leads us to assume that the latter might not be the case. Additionally, our study was retrospective, and thus, prone to reporting and recall bias. Specifically, effects related to self-reported memory problems may be partly explained by reporting bias, as participants who were football players, frequent headers or had a history of concussion may be more inclined to report impairments. However, differences in memory performance were also observed on objective measures and overall performance motivation was high among retired athletes. Further, there is valid concern about the accuracy of the retrospective assessment of concussion histories and heading exposures.[73] As described above, other studies have chosen to use playing position as a proxy for heading exposure, which some might argue is the more objective operationalisation. Indeed, heading studies show that there are systematic differences across playing positions with defenders typically heading the ball most frequently.[74] However, as other individual factors such as height and specific motors skills also play a role in heading frequency, we chose an individual self-report approach.

CONCLUSION

This is the first study on potential long-term effects of sport-related concussions in women, and thus, provides highly relevant information on a topic previously only explored in men. Our main finding was that retired elite female football players and non-contact sport controls perform similarly on most neurocognitive test domains with exception of verbal memory and fluency, where football players performed significantly weaker. These differences in verbal memory and fluency may be related to a history of multiple concussions and frequent heading. However, as the presented evidence cannot speak to causation, more research on the topic involving (retired) female athletes is clearly needed. In light of our own results and findings from other current research,[15 65 67] studies assessing various memory variables in more depth, with older age groups and a larger sample size would be particularly insightful. Additionally, studies employing a prospective research design are important to address the question of causality. In order to facilitate such large-scale prospective studies over several decades and provide the research field with more certainty, sustained funding from sport associations and state institutions will be essential.

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