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A pilot study of diffusion tensor imaging metrics and cognitive performance pre and post repetitive, intentional sub-concussive heading in soccer practice

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Abstract

Background: Although soccer players routinely head the ball in practice and games, recent research has suggested that cumulative effects of repetitive heading may cause sub-concussive injury with accompanying effects on brain and behavior. The current study aimed to prospectively investigate the effects of repetitive, intentional heading in soccer practice on brain structure and cognitive function, using a within-subjects design.

Methods: Participants included 10 soccer players (mean age 20.09 years ± 2.88) who were examined immediately pre- and post-heading practice. An accelerometer was used to measure the force of the impact during soccer heading. Magnetic resonance imaging data were acquired on a 3 T GE Scanner with diffusion tensor imaging. Diffusion tensor imaging analyses were completed using functional magnetic resonance imaging of the brain software library's Tract-Based Spatial Statistics to examine changes in both fractional anisotropy and mean diffusivity due to heading the soccer ball. Behavioral measures were also completed pre- and post-soccer heading and included the Sport Concussion Assessment Tool and three short-computerized executive function tasks; R studio was used to compare behavioral data within subjects.

Results: Accelerometer data revealed that none of the heading impacts were $>10g$. At this level of impact, there were no significant pre–post heading differences in either fractional anisotropy or mean diffusivity. Additionally, aside from minimal practice effects, there were no significant differences in Sport Concussion Assessment Tool scores and no significant differences in the performance of the three executive function tasks pre–post heading.

Conclusions: The results provide initial evidence that repetitive heading in soccer practice, at a g force of 10, does not cause changes in brain structure or executive function. Future research should investigate heading in the context of games and with a greater sample size that would allow for sex-based comparisons.

Keywords

Sub-concussive, heading, soccer, sports, diffusion tensor imaging, executive function, SCAT-3

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Introduction

Soccer is a unique sport given that players purposefully and voluntarily use their unprotected heads to manipulate the direction of the soccer ball for both offensive and defensive plays.[1] Recent studies have reported that players typically head the ball up to 12 times per game, with the ball traveling upward of 80 km/h.[2] Conversely, heading in practice generally consists of repetitive, low-velocity impacts with a focus on skill development.

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Nevertheless, data from simulated heading drills, with the ball traveling approximately 43 km/h, estimate linear acceleration of the head at a gravitational force of 15–20*g* and an angular acceleration between 1000 and 2000 rad/s.[2,3] Although there is no consensus regarding the g force that may lead to a concussion, study estimates have ranged from as low as 40*g* to as high as 100*g*.[4–9] In any case, with a maximum estimated impact of 20*g* measured with soccer heading practice, the forces involved fall well below those considered to be required for a concussive impact.

A growing area of concern in soccer is that the repeated sub-concussive impacts through heading the ball may have a cumulative effect and produce long-term neurological damage. Sub-concussive impacts can be defined as blows to the head that do not cause typical concussion symptoms or result in a diagnosed concussion.[10] Sub-concussive effects may also occur with rapid-acceleration–deceleration of the body and torso causing the brain to move within the cranium.[11] The key part of any definition of sub-concussive impacts is that there are no immediate symptoms reported and no outward signs of neurological dysfunction; these impacts do not register as a concussion on clinical levels, but they can be accompanied by neurochemical changes in the brain (Broglio et al.[5]).

The role of heading received significant attention when a coroner ruled the cause of death of Jeff Astle, a former English international player. Astle was a center forward who turned professional at age 17. Astle played professional soccer from 1959 to 1977, with a brief stint on the English National Team in 1970. Astle was known for his heading during his playing career. After Astle's death in 2002, a coroner remarked the presentation of Astle's dementia may be the result of cumulative and repetitive brain impacts that may be consistent with heading the ball during his career.[12] It was noted that the frontal lobes of Astle's brain showed 'shrinkage and softening' and that the trauma to the brain was consistent with that of boxers. Importantly, boxers were the first athletic population to be diagnosed with chronic traumatic encephalopathy (CTE), otherwise known as dementia pugilistica, due to repetitive, traumatic head impacts.[13–16] CTE is a degenerative brain disease, caused by repeated head trauma, that results in the atrophy of brain tissue.[17] While the diagnosis suggests heading as a cause of death, there has not been enough evidence separating heading from other head impacts in soccer, nor have there been any studies showing a causal link between heading and any form of neurological damage.

Most research to date has considered sub-concussive impact in the broader context of sport-related injury. The largest review to date[18] examined sub-concussive head impacts across five sports (football, soccer, hockey, boxing, and lacrosse) in a total of 59 studies. Interestingly, 14 studies provided support for possible structural changes in players with repeated head trauma without concussion symptoms, including changes in white matter microstructure, decreased cortical volume, and cortical thinning. There were mixed findings in the relationship between brain structure and cognitive performance, in part due to the inconsistency of measures used across studies. Mainwaring et al.[18] concluded that in male athletes, repetitive hits to the head present risk of microstructural and functional changes to the brain, and repetitive head impacts in sports should be avoided.

To date, there have been three studies that have focused specifically on changes in brain structure related to heading in soccer, and each of them used magnetic resonance imaging (MRI)-based approaches. Two studies examined professional male soccer players with long-term heading exposure; Koerte et al.[19] found widespread cortical thinning in soccer players compared with controls and Jordan et al.[20] found no long-term effects. Notably, the MRI measures used in both of these studies are not sensitive to changes in brain structure following concussion, as are more advanced imaging techniques such as diffusion tensor imaging (DTI).[21] DTI is an MRI-based technique that is sensitive to differences/changes in white matter microstructure, as measured by decreased fractional anisotropy (FA) and increased mean diffusivity (MD) when white matter integrity is compromised. Given that DTI measurements have been particularly sensitive to microstructural changes in white matter associated with concussion, for example, Virji-Babul et al.,[22] this acquisition technique may be particularly appropriate for investigating sub-concussive impacts. Congruently, results from a landmark study by Lipton et al.[23] revealed that short-term high-frequency heading was associated with lower FA in temporal and occipital regions. This study was particularly important because it established a relationship between exposure to heading and changes in both brain structure and function. Taken together, in a recent review, Rodrigues et al.[1] reported preliminary evidence of abnormal brain structure as a result of heading and concluded with a strong emphasis on the need for future studies with longitudinal designs.

More research to date has focused on the relationship between soccer heading and changes in brain function, as measured by neuropsychological assessment measures and cognitive tasks. In the most recent review, which included 15 studies, Tarnutzer et al.,[24] reported that the frequency of heading was not strongly associated with any neuropsychological impairments. Importantly, they reported that eight studies did not detect significant differences in cognitive performance between soccer players and controls,[19,25–30] while seven studies reported significantly lower performance scores for soccer players in at least one test.[19,20,23,31–35] These mixed results may have resulted from the wide variety of assessment measures employed across studies. Tarnutzer et al.[24] noted that the cognitive domains that are most commonly affected are executive function and memory, providing direction for future studies. Executive function (our ability to coordinate goal-directed action and cognitive processing), in particular, seems to be the most vulnerable to the effects of concussions in adolescents,[36] but there is scarcity of research examining in depth the effects of soccer ball heading practice on this higher-order function.

The present study used a prospective within-subject design to investigate the influence of repetitive heading during soccer practice in youth players using a multimodal approach to examine both brain structure (as measured by DTI) and function (as measured by standard concussion measures and tests of executive function).

It was hypothesized that there would be decreased microstructural integrity of white matter after soccer heading practice. The current study also examined if participants would show increased reaction time on tasks of executive function, and change in their Sport Concussion Assessment Tool (SCAT-3) scores, particularly greater concussion symptoms and increased standard assessment of concussion (cognition) scores, after soccer heading practice.

Materials and methods

Study design

The study involved participants acting as their own controls and participating in both study conditions. The study took place over two consecutive days, with MRI scan occurring within approximately 36 h of each other. The travel time between West Coast Medical Imaging, where the MRI was completed, and the soccer pitch was no more than 10 min. On day 1 pre-heading (baseline) data were collected and on day 2 post-heading data were collected (Figure 1). On day 1, participants first had their MRI scans done to establish baseline. On day 2, participants had their MRI after the heading drill to capture post-heading brain scans. The sequence of events was consistent on days 1 and 2 except for the MRI, except catching was replaced with heading on day 2. The study was approved by the Human Research Ethics Board at the University of Victoria.

Participants

Youth participants, aged 15–25, were recruited from Victoria, BC. Participants were included in the study based on the following inclusion/exclusion criteria: current soccer players (either currently playing or between seasons), no current head or neck injury, no neurological conditions, and no concussion or concussive symptoms within the last 6 months (to ensure that participants were not presenting with intermittent concussion symptoms).

Soccer drills

The drills consisted of five components: (1) 8-min rest, (2) catching or heading, (3) 8-min rest, (4) 8-min steady-state exercise, and (5) the SCAT-3 (details below). These components were completed on both days, with catching on day 1 for baseline and heading on day 2.

1. *Rest*. During the rest period, participants were instructed to lie completely still for 8 min. Participants kept their eyes closed and wore ear plugs to minimize environmental noise to ensure complete rest.
2. *Catching*. A set of cones were spaced 3.65 m apart measured with a measuring tape. Participants, in pairs, stood at each end and completed two sets of five catches, switching positions after each set of five. This maintained consistency of direction. The ball was thrown using an underhand toss and participants were instructed to remain standing and catch the ball in front of their heads. Catching the ball right in front of the participants' heads ensured a movement that mimicked a header, without actual ball impact to the head. The ball, a regulation size 5, was inflated to regulation pressure, between 8.5 and 15.6 PSI.
   OR
   Heading. A similar set-up was used for the heading component on day 2. Participants maintained a 3.65 m distance and switched positions after every set of five headers, completing two sets each. Participants threw the ball to each other as they would in a standard soccer practice. Ten impacts were selected to mirror drills performed in standard local soccer practices. Participants were again instructed to head the ball from standing. Participants wore an accelerometer (Triax SIM-P) in a headband to measure the force of the soccer ball. The accelerometer was calibrated before each use by resetting the device. The accelerometer was tested before use to ensure accuracy. The headband was worn with the accelerometer positioned on the back of the head to avoid direct impact with the soccer ball. The accelerometer recorded impacts $>10g$. If the accelerometer did not record a force measurement, impacts were noted to be $<10g$.

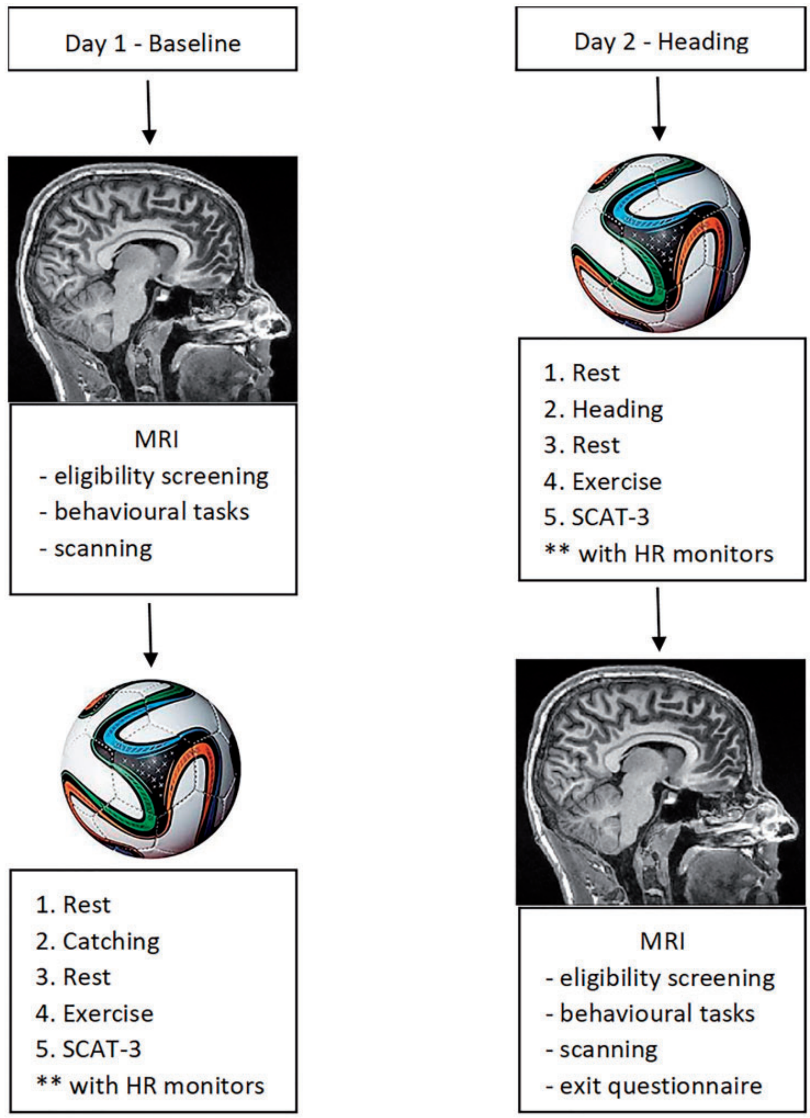

Figure 1. Pre-heading (day 1; baseline) and post-heading (day 2) study design. Cartoon depicting the sequence of events for subjects across the 2 days of testing is shown. On day 1 subjects completed intake forms and were evaluated for eligibility prior to undergoing an initial MRI scan. Following the initial scan, subjects completed a short series of behavioral tasks that did not involve heading (only hand catching), and were administered a SCAT-3. The following day subjects underwent the same behavioral testing procedure, but engaged in heading practice, and then were administered a SCAT-3, an MRI, and behavioral testing.
MRI: magnetic resonance imaging; SCAT-3: Sport Concussion Assessment Tool.

Proper technique was monitored throughout, and improper headers were recorded. If participants did not make contact with the ball on a throw or missed on a header, an additional header was added to the rotation. For example, if header number three was missed, then the total number of headers would be 11.

3. *Rest*. A second 8-min rest period followed the catching or heading portion of the day.
4. *Steady-state exercise*. Cones were set up 20 m apart. Participants maintained a constant speed of 20 m in 8 s (2.5 m/s) using a HIIT Interval Training App with audible reminders. Participants ran at this speed maintaining steady-state for 8 min.
5. *SCAT-3*. At the end of the drills, the SCAT-3 was conducted using standardized instructions for administration and scoring for each section.

Neuroimaging data acquisition

A 3T GE MRI scanner at West Coast Medical Imaging facility in Victoria, BC, was used for neuroimaging data collection. Scanning sessions were approximately 30 min per person at each time point. The DTI scan parameters were as follows: acquisition matrix = 256 × 256, voxel size = $1.4 \times 1.4 \times 2.0\,mm^3$, TR = 8000 ms, flip angle = 90°, number of slices = 52. There were 48 images acquired for each scan: 45 diffusion-weighted images ($b = 1000\,s/mm^2$) and 3 non-diffusion-weighted images ($b = 0\,s/mm^2$).

Neuroimaging data analyses

The DTI data were analyzed using Functional MRI of the Brain Software Library (FSL) version 5.0 (Analysis Group, FMRIB, Oxford, UK, http://fsl.fmrib.ox.ac.uk; (Smith et al.[37])).

During pre-processing, diffusion weighted images were corrected for head movement and eddy current distortions using Eddy Current Correction, and the skull was removed using Brain Extraction Tool. DTIfit was used to create FA and MD maps of each individual brain image. Once all FA maps were created, the data were processed with FSL's Tract-Based Spatial Statistics (TBSS) pipeline to obtain a mean FA skeleton from the projection of all participants' FA data.[38] Participants' FA data were nonlinearly aligned to 1 × 1×1 mm standard space. Once all individual FA images were aligned to standard space, the mean FA image was created and thinned (threshold FA = 0.2) to generate the mean FA skeleton. A 4D image file was created with each participant's FA data projected onto the thresholded mean FA skeleton.

Voxel-wise statistical analyses of the skeletonized FA data were performed using the Randomize function, FSL's nonparametric permutation inference tool with threshold-free cluster enhancement to correct for multiple comparisons ($p < 0.05$). In addition to FA data, TBSS analyses were also performed for MD files in a similar fashion. Nonlinear registration was applied to the MD data, and all the participants' MD data were merged into a 4D file. Each participant's MD data were projected onto the mean skeleton before applying the same voxel-wise statistics. Data were analyzed at the whole-brain level for within-group differences pre–post heading practice (day 1 and day 2).

Behavioral data acquisition

Examination of executive functioning requires a multidimensional approach, and the most robust model includes three components: shifting, updating working memory, and inhibiting (Karr et al., 2018; Miyake et al., 2000). For this purpose, three behavioral tasks were administered prior to each neuroimaging session (created in MATLAB): the n-back task (updating), the More Than–Less Than/Odd–Even task (shifting), and the Go/No-Go Task (inhibiting). Accuracy and reaction time were collected for each task. To assess each participant's level of inhibitory processing, a traditional and well-established go/no-go paradigm (Donders, 1868, 1969) was used to measure the inhibition of a prepotent response. The n-back task is a commonly used measure of working memory capacity (Conway et al., 2005). The test is designed to demonstrate how adept subjects are at updating, holding, and discarding information. Although this has been criticized due to low reliability of the scores, it is recognized as one of the most useful tools for the experimental assessment of working memory (Jaeggi et al., 2010), To examine shifting ability, participants completed a More Than/Less Than Task (i.e. deciding whether a digit is more or less than 5) and an Odd/Even Task (i.e. deciding whether a digit is odd or even; Friedman et al., 2007).

During the n-back task, participants were shown a series of letters one at a time on the computer screen. Participants indicated when the current letter matched the letter shown either 1 or 3 trials before. There were 4 blocks with a total of 150 trials. Between each trial a blank screen was shown (for 1.5 s), and total time for the task was approximately 6 min.

The More Than–Less Than/Odd–Even task consisted of multiple trials where a single white digit was displayed on a black background on the computer screen. A new digit appeared for each successive trial; the digit disappeared after the participant provided a response. Depending on the task, the words 'More Less' or 'Odd Even' were displayed below the digit to provide a prompt to the participant regarding the task. For the full shifting condition, these two tasks were combined and required participants to switch from one task to another when a white rectangle surrounds the displayed number. This task consisted of six total blocks; the first two blocks had participants perform the same task (i.e. either all *More*/*Less* or all *Odd*/*Even*) while the third to sixth blocks included 10 task-switch trials. Switch trials will occur randomly, with a minimum of 7 to 13 non-switch trials in between each switch. This task took approximately 6 min to complete.

To Go/No-Go task consisted of two blocks of 50 and 150 trials, respectively; in the first block, participants were asked to respond as quickly as possible to any letter appearing at the center of the computer screen by pressing the spacebar to create baseline reaction times. In the second block, participants were asked to do as they did in the first block except they were instructed to refrain from responding when the letter 'j' appeared. Task completion time was approximately 6 min.

Behavioral data analyses

The statistical program R was used for behavioral data analyses (R Core Team, 2013). Between-group comparisons were made between day 1 and day 2 for all three computer tasks and for the SCAT-3 using separate between-group paired *t*-tests. Each component of the SCAT-3 was compared independently: total number of symptoms and symptom severity were analyzed and compared together, cognitive assessment (SAC) scores were compared, and balance scores were compared.

Results

Participants

Eleven participants were recruited for this study, three females and eight males; however, one participant was unable to have an MRI scan (due to braces), one participant was unable to complete the exercise portion (due to a lower body injury) and one participant's MRI data had an artifact that could not be corrected. The participant characteristics are summarized in Table 1.

Accelerometer data

The Triax SIM-P accelerometer was set to record any impacts $>10g$. The heading portion of the soccer drills never exceeded the minimum threshold of $10g$, thus no impacts $>10g$ occurred for any participants in the study.

DTI data

There were no significant differences in FA or MD post-heading compared to pre-heading the soccer ball (Table 2).

Behavioral data

There were no significant differences in reaction time post-heading compared to pre-heading practice on two versions of the n-back, the Odd–Even task, and the Go–No Go task (Table 3). On the More Than–Less Than task, post-heading reaction times were significantly lower than pre-heading practice reaction times (Table 3).

There were no significant differences between number of SCAT-3 symptoms, symptom severity, or balance scores post-heading compared to pre-heading practice (Table 4). There was a significant difference between pre- and post-heading Standard Assessment of Concussion SCAT-3 scores measuring cognition, such that post-heading scores were greater than baseline.

Discussion

The current study aimed to investigate the effects of heading in young adult soccer players, using a

Table 1. Summary of participant characteristics.

Characteristic	Group ($n = 11$) Mean (SD)	Females ($n = 3$) Mean (SD)	Males ($n = 8$) Mean (SD)
Age (years)	20.09 (2.88)	20.33 (4.51)	20 (2.45)
Height (cm)	178.61 (8.45)	172.97 (12.27)	180.72 (6.34)
Weight (kg)	76.45 (12.33)	69.85 (15.60)	78.93 (11.04)
Years playing	11.36 (4.25)	13.33 (6.66)	10.63 (3.29)
Past concussions	1.45 (1.75)	1	1.63 (2.07)

Table 2. DTI metrics at the whole brain level for each participant.

	Whole brain FA		Whole brain MD	
Participants	Pre-heading	Post-heading	Pre-heading	Post-heading
1	0.55480713	0.549174559	0.000712334	0.000715493
2	0.502629434	0.499646352	0.000781202	0.000771834
3	0.526287503	0.529831455	0.000716538	0.000713659
4	0.535925581	0.533491731	0.000728713	0.000718868
5	0.5371087	0.540753377	0.000703857	0.000702866
6	0.515378546	0.51737795	0.000731903	0.000731539
7	0.54868143	0.556450277	0.000683075	0.000692671
8	0.534148043	0.519966366	0.00073616	0.00072788
9	0.5198314	0.532746025	0.000754906	0.000744642

DTI: diffusion tensor imaging; FA: fractional anisotropy; MD: mean diffusivity.

Table 3. Pre- and post-heading reaction time data (Mean, SD, and *P*-values).

Measure	Pre-heading Mean	Pre-heading SD	Post-heading Mean	Post-heading SD	*p* Value
1-back	0.4189	0.06696	0.4025	0.05259	0.2298
3-back	0.597659	0.08242	0.56317	0.07413	0.2027
More/Less Than	0.546	0.0.058	0.462	0.0439	0.0024
Odd–Even	0.628	0.139	0.563	0.112	0.1115
Switch condition	0.8427	0.185	0.6179	0.219	0.04695
Go–No Go	0.3495	0.0310	0.3559	0.0250	0.2628

SD: standard deviation.

Table 4. Pre- and post-heading SCAT-3 data (Mean, SD, and *P*-values).

SCAT-3	Pre-heading Mean	Pre-heading SD	Post-heading Mean	Post-heading SD	*p* Value
Symptoms	2.545	4.03	1	1.67	0.130
Severity	2.727	4.15	1.3	1.78	0.144
Standard assessment of concussion	27.182	1.47	28.545	1.04	0.001
Balance errors	3.273	3.37	2.182	1.99	0.1186

SCAT-3: Sport Concussion Assessment Tool; SD: standard deviation.

multimodal approach to examine brain structure and function. It was hypothesized that reduced white matter integrity would be demonstrated after soccer heading practice and that changes in brain function would be found alongside changes in brain structure. Conversely, there was no evidence of changes in brain structure or function associated with soccer heading practice.

Brain structure and heading

The results suggest that repetitive heading in soccer practice, at a force $<10g$, does not contribute to structural changes, given that there were no significant differences in FA or MD post-heading compared to pre-heading practice. In the whole brain level analysis, both FA and MD values were not significantly different between sessions and were in line with values seen in healthy individuals of the same age.[39]

The current study represents the first to investigate heading in a controlled soccer practice setting with pre–post assessments of the brain at a microstructural level. Previous research has used questionnaires and observations to measure the frequency of heading in soccer practice or games without controlling for the force of the impact or number of headers. The only other DTI study that has used DTI metrics to examine soccer heading found decreased FA in temporal–occipital white matter.[23] However, in the Lipton et al.[23] study, heading was quantified using self-report measures that captured an average of 442 headers over the previous 12 months. Interestingly, the reported brain abnormalities were seen opposite of heading impact suggesting a countercoup injury. It is possible that sub-concussive injuries causing changes to brain structure occur over a longer time frame with a greater number of impacts, are more likely to occur in games, and occur with higher gravitational force than measured in the current study.

Brain function and heading

The results of the current study indicate no acute cognitive changes occur after a bout of heading in a soccer practice setting. Specifically, there was no evidence of decreased cognitive function after soccer heading practice as measured by three executive function tasks and the SCAT-3. In fact, there were occasions in which post-heading scores appeared to improve, which may be interpreted as practice effects. These results are consistent with previous soccer heading research, which has indicated that changes in performance on cognitive tasks may be subtle and difficult to detect, explaining why the literature to date is quite mixed.[6,31,32,40,41] According to recent systematic reviews, the mixed results seem to stem from the variability of neuropsychological tests used in each study.

Similar to measures of cognitive function, the effects of heading on concussion-like symptoms (as commonly measured by the SCAT) are mixed; some studies identify an increase in symptoms after bouts of heading,[25,42,43] while others indicate no changes pre and post heading.[26,44] Notably, the SCAT has undergone several revisions over time, and the SCAT-3 in the current study has been replaced by the SCAT-5. Moving forward, future studies should strive to incorporate common measures of cognition and other symptoms in order to compare results between samples and allow for stronger more powerful conclusions.

Strengths

This study used a multimodal approach, encompassing both brain structure and function, to analyze the effects of repetitive heading. The protocol was optimized to limit potential confounding variables. Participants acted as their own controls in a design that has been called for by recent reviews.[1] Pre- and post-heading MRI scans were obtained within 24 h of each other and MRI scan post-heading was obtained immediately after heading practice (participants went directly from the field to the MRI scanner). The heading protocol used in this study also mimicked a heading drill that is regularly used by soccer teams in practice.

Limitations

The main limitation of the current study was the small sample size. Future studies should aim to include larger numbers of participants to address any possible issues related to low power. Notably, the current study focused on a practice setting and results cannot be extrapolated to games, which typically have a fewer number of headers with greater velocities and head acceleration (i.e. greater $>10g$ forces involved). Additionally, the current protocol included 10 headers, which is representative of the number that occurs in practice, but not across a season. The condensed schedule of the current protocol was designed to minimize confounding variables, but the study did not directly control for participating in other activities that could have impacted brain structure or function. Finally, the current study did not include a control group to measure baseline differences in brain structure that may have related previous soccer play.

Future research

Based on the shortcomings of the current study, an ideal study would have a larger, heterogeneous sample size and focus on youth athletes. A larger sample size would improve the strength of the study results (by improving the power) and allow for greater control over concussion history. Additionally, it would be ideal to investigate sub-concussive impacts as a function of sex, given that neck girth and strength (which are lower in females) can affect the kinematics of heading.[45] A study by Klein et al. (2019) found that female athletes are more likely to demonstrate MRI changes post-concussion. It would also be ideal for future studies to focus on the effects of sub-concussive impacts over a longer period of time (e.g. pre–post season, rather than pre–post practice). Such studies should include multimodal data collection, including accelerometer data, broader measures of cognition (e.g. including both executive function and memory), and metrics of both brain structure and function will be key for drawing robust conclusions. Such studies could influence our understanding of when heading the ball may be safe (e.g. in conditions of low velocity, as in the current study) and when it may have negative consequences (perhaps when the ball is headed at high velocities during games or many times over the months of a season). Finally, longitudinal studies that evaluate the effects of repetitive heading over the course of multiple seasons and years of playing will be important to establish the long-term effect of heading in soccer, which may become increasingly evident over decades.

It should be noted it is possible that other advanced MRI techniques, such as myelin water imaging, may be more sensitive than DTI to detecting microstructure changes following sub-concussive impact (Weber et al., 2018). Future research could add additional techniques to study the effects of sub-concussive effects on soccer players.

Conclusions

Due to the limited and inconclusive nature of previous research into effects of heading in soccer, the current study utilized an innovative multimodal protocol to examine the effects of soccer heading practice within-subjects. Based on the current data, heading the ball at a force up to $10g$ 10 times during a soccer practice does not seem to be a health hazard for changes in brain structure and cognitive function. Future research should continue to examine sub-concussive impacts associated with soccer heading, using a multimodal approach in larger samples over time to investigate both acute and longitudinal effects.

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