SHOULD WE LOSE SLEEP OVER SLEEP DISTURBANCES AFTER SPORTS RELATED CONCUSSION? A SCOPING REVIEW OF THE LITERATURE

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ABSTRACT

Objective. A single, severe traumatic brain injury can result in chronic sleep disturbances which can persist several years after the incident. By contrast, it is unclear whether there are sleep disturbances after a sports-related concussion (SRC). Considering growing evidence of links between sleep disturbance and neurodegeneration, this review examined for potential links between diagnosed SRCs and sleep disturbances to provide guidance for future studies.

Methods. The scoping review undertook a systematic search of key online databases (Scopus, MEDLINE, SportDiscus and Web of Science) using pre-determined search terms for any papers that examined sleep after concussion. A screening criterion using agreed inclusion and exclusion criteria was utilised to ensure inclusion of relevant papers.

Design. This scoping review is guided by the PRSIMA Scoping Review report.

Results. Ten studies met the inclusion criteria, reporting on 896 adults who had experienced a SRC. Comparison to 1327 non-SRC adults occurred in eight studies. Nine studies subjectively examined sleep, of which all but one study reported sleep disturbances after a SRC. Three studies objectively measured sleep, with two studies indicating large coefficients of variation of sleep duration, suggesting a range of sleep responses after a SRC. The only study to examine overnight polysomnography showed no differences in sleep metrics between those with and without a SRC. No studies examined interventions to improve sleep outcomes in people with concussion.

Conclusions. This scoping review indicates preliminary evidence of sleep disturbances following a SRC. The heterogeneity of methodology used in the included studies makes consensus of the results difficult. Given the mediating role of sleep in neurodegenerative disorders, further research is needed to identify physiological correlates and pathological mechanisms of sleep disturbances in SRC related neurodegeneration, and whether interventions for sleep problems improve recovery from concussion and reduce the risk of SRC related neurodegeneration.

Keywords. Sleep, sleep wake disorders, brain concussion, craniocerebral trauma, chronic traumatic encephalopathy, athletic injuries

INTRODUCTION

Sport-related concussions (SRC) is a form of mild and/or minimal traumatic brain injury[1] that is an ever-present concern for participants in many sports.[2] Participants in collision sports, such as ice hockey,[3] American football,[4] and both rugby union and rugby league,[5,6] are particularly are risk of experiencing a SRC. Furthermore, many athletes report experiencing multiple concussions throughout their career.[7,8] Yet, the incidence and impact of SRCs may be underestimated, as 40-60% of concussion events go undiagnosed or unrecognised.[9]

A concussion results from biomechanical trauma to the head, such as a direct impact, or a sudden indirect acceleration, deceleration and/or rotation of the head with or without the loss of consciousness.[10] The biomechanical trauma causes shearing and/or tearing neuronal axons, leading to a neurometabolic cascade which results in altered resting states and brain activation patterns.[11,12]

The chronic adverse health impacts of repeated SRCs are rapidly becoming a public health concern.[13] Acutely, concussion can result in a broad spectrum of physical, emotional, and cognitive symptoms.[14] Furthermore, there is growing evidence that those exposed to repeated concussions may experience 'chronic traumatic encephalopathy' (CTE) in later life.[15] CTE is typified by the excess accumulation of amyloid-β and τ-proteins, which are implicated in neurodegenerative disorders including Alzheimer's disease, Parkinson's disease, and amyotrophic lateral sclerosis.[16,17] Yet how repeated SRCs and the development of CTE are associated still needs to be established.[18] One possible explanation implicates sleep disturbances, as even a single night of sleep deprivation results in the accumulation of amyloid-β and τ-protein.[19,20] Current evidence indicates that disruptions of slow wave sleep interrupts the clearance of amyloid-β and τ-protein by the glymphatic system, resulting in accumulation of amyloid-β and τ-proteins.[21] Unsurprisingly, sleep disturbances, such as irregular sleeping schedule and irregular sleeping hours, as well as clinical sleep disorders such as obstructive sleep apnea, and insomnia, are considered primary risk factors for neurodegenerative disorders due to the disruption of SWS.[22-25]

Between 30-66% of traumatic brain injury survivors report sleep disturbances, such as trouble initiating and/or maintaining sleep, or symptoms of hypersomnolence, such as sleeping for excessive periods of time (i.e., sleeping more than the recommended seven to nine hours a night), which persist for several years after the initiating event.[26] Whilst sleep disturbances are widely recognised as symptoms of concussion,[27,28] our understanding of the relationship between sleep and concussion is much more limited. Thus, a scoping review on the association of SRCs with sleep in adults was undertaken to establish the extent of research in the area, with the aim of establishing a preliminary evidence-based synthesis of the topic, and to provide directions for future research in the area.

METHODS

This paper follows the PRISMA Extension for Scoping Reviews guidelines.[29] To our knowledge, there has been no literature or systemic reviews examining the effect of SRC on sleep, therefor a scoping review was conducted. A scoping review would identify the current scope of research, and therefore any knowledge gaps, as well as establish the methodologies used, all whilst still undergoing a rigorous and transparent methodology.[30-32] Scoping reviews are not eligible for PROSPERO registration.

Our primary research question was '*Are there sleep disturbances after experiencing a sport-related concussion?*'. We limited the scoping review to adults (18 years of age and over) due to the differences in sleep patterns and sleep disorders between adolescents and adults.[33,34] Furthermore, to assess the characteristics of the methodologies used, the secondary research question was '*What are the methodological characteristics of studies examining the effect of concussion on sleep, namely; how was sleep assessed, how was concussion assessed, the study design, and populations used?*'.

Scopus, MEDLINE (via PubMed), SportDiscus and Web of Science databases were systematically searched from inception to identify potentially relevant studies. Utilising key words around SRC, sports, and sleep, as well as using Boolean operator terms, the search terms were ((“concus*” OR “mild traumatic brain” OR “mTBI”) AND (“sleep” OR “circadian” OR “insomnia” OR “sleep disord*” OR “sleep dist*” OR “obstructive sleep”) AND (“athletes” OR “rugby” OR “football” OR “AFL” OR “NFL” OR “contact sport” OR “collision sport”)). Where available, filters to remove review papers, editorials, and conference abstracts, as well as non-English language documents, were applied. An initial search was undertaken in November 2019, with a second search completed in September 2020.

English language, prospective and retrospective cohort studies, and randomised controlled trials which examined SRC induced changes to sleep or interventions to improve sleep after a SRC were eligible for inclusion. Review papers, editorials, and conference abstracts were excluded.

Eligible studies included adults (>18 years) that suffered a concussion during athletic performance. Concussion was required to be identified either by professional diagnosis, a concussion assessment tool (e.g., Sports Concussion Assessment Tool), or explicit participant declaration of a previous medically diagnosed concussion. Studies examining concussion in children (< 18 years), animal models of concussion, or concussion acquired outside athletic performance were excluded.

Sleep outcomes included any subjective or objective measures of sleep. Eligible subjective measures included standardised questionnaires, such as the Pittsburgh Sleep Quality Index (PSQI),[35] or individual sleep-related items from a validated diagnostic tool, such as the Sports Concussion Assessment Tool (SCAT),[36] or specific questions pertaining to sleep but not part of any validated questionnaire. Eligible objective sleep assessments were either actigraphy or polysomnography (PSG). Actigraphy is a device worn on the body that uses accelerometery to determine sleep by extended periods of non-movement.[37] PSG collects neurophysiological data to determine total sleep time, wake after sleep onset, sleep efficiency, and how much each stage of sleep (Stages 1, 2, slow wave sleep, and rapid eye movement sleep) contributes to overall sleep for a specific night.

Eligibility of the studies were evaluated independently by two authors (DS and AA), with disagreements between reviewers arbitrated by a senior author (LH). After removing duplicates, the titles and abstracts of all studies were screened. Those considered potentially eligible were read in full to determine inclusion. In studies with insufficient published information, the corresponding author of that paper was contacted.

For articles meeting all inclusion and no exclusion criteria, two of the authors (DS and AA) extracted data based on the following categories:

1) Primary author and year of publication

2) Number and gender of concussed and control participants

3) Mean age; of entire cohort, and for all concussed and all controls

4) Study design;

i) Within subjects (pre-post assessment), between participants (separate control group), or observational (no control group).

ii) Prospective (participant recruited either to monitor incidence of concussion or were recently concussed, and were still recovering), retrospective (participants who previously experienced a concussion, and were no longer symptomatic),

iii) or RCT (induced sleep change or treated sleep complaint).

4) Concussion specifics,

i) diagnostic method and criteria (physician, assessment tool, self-report)

ii) number of concussions

iii) time between concussion and sleep measure

5) Sleep measurement; subjective and objective

Table 1. Synthesis of the extracted data from the of the included studies

Study	Participants	Mean age (yrs)	Study design	Concussion specifics	Sleep measurement	Outcome
Blake 2019 *(ref 38)*	Cohort = 82 (f = 52) Concussion = 42 (f = N/A) Sports Baseball Soccer Softball Ultimate frisbee Athletics Rugby Lacrosse Volleyball Basketball Field hockey Other	Cohort = 20.3 (±1.5) Concussion = **NA**	Retrospective Between participants	Dx: Self-report 40/82 report 0 concussions 29/82 report 1-2 concussion 13/82 reported 3+ concussions Concussion Definition: **NA** Symptoms: Rivermead Postconcussion questionnaire	Subjective: Self-report of common symptoms (not-validated); difficulty falling asleep, restlessness, sleeping too much, sleeping too little, difficulty staying asleep, fatigue Sleep measures relative to most recent concussion - **NA**	Differences between groups (p=0.028). Post-hoc analysis showed 3+ prior concussions significantly more sleep disturbances vs 0 concussions (p = 0.012). No other differences reported. Prevalence of sleep disorders for each concussion group was not reported.
Churchill 2017 *(ref 39)*	Control 35 (f=19) Concussed 35 (f = 19) Sports Volleyball Hockey Soccer Football Rugby Basketball Lacrosse	Concussed = 20.3 (±2.2) Control = 20.3 (±1.7)	Prospective Between and within participants	Dx: Physician Definition: Concussion in Sport Group (*ref 36)*	Subjective: Fatigue and sleep symptom questions of the SCAT-3; fatigue/low energy, drowsiness, trouble falling asleep Sleep measures relative to most recent concussion - 3.6 (±1.2) days	No difference in fatigue and sleep symptom severity from pre- to post-injury for the concussed participants (p=0.36), nor differences between concussed post-injury and to non-concussed controls (p=0.16).
Davis-Hayes 2017 *(ref 40)*	Cohort = 1200 (f = 378) Concussed = 228 (f = 88) Sports Football Wrestling	Cohort = 19.0 (± 1.0) Concussed = N/A	Prospective (retrospective analysis of cohort) Between participants	Dx: Physician Definition: Concussion in Sport Group (*ref 36)*	Subjective: Sleep disturbance questions from the 'Headminder Concussion Resolution Index System' ^ Sleep measures relative to most recent concussion – <24 hours	29% males and 42% of females reported sleep disturbances. Actual sleep disturbances not reported. Females incidence was significantly higher than male (p=0.048). *Symptomology only examined after the first concussion, meaning no*

	Soccer Basketball Field Hockey Lacrosse Baseball Volleyball Softball					*comparison to non-concussed controls*
Gosselin 2007 *(ref 41)*	Control = 11 (f = 4) Concussed = 10 (f = 3) <u>Sports</u> Soccer Football Hockey Rugby Skate (*described in text as part of a "skate team"*)	Control = 22.6 (± 2.4) Concussed = 24.3 (± 6.1)	Retrospective Between participants	Dx: Self-report of physician diagnosis Definition: World Health Organisation collaborating centre for traumatic brain injury (*ref 51)*	Objective: PSG, which measured; total sleep time (mins), sleep onset latency (mins), wake after sleep onset (mins), arousal index, sleep efficiency (%), individual sleep stage (N1, N2, deep, and rapid eye movement [REM])%, REM onset (mins), REM efficiency. Subjective – sleep quality (PSQI), daytime sleepiness (ESS). Sleep measures relative to most recent concussion - 1-11 months	No group differences in any PSG measures (p values not reported) Concussed participants significantly worse quality sleep (PSQI: 7.7±3.8 vs 3.5±2.3, p = 0.006), no difference in sleepiness (9.9±6.1 vs 9.6±6.1, p value not reported)
Gouttebarge 2017 *(ref 42)*	Cohort = 576 Concussion = 363 *All participants were male.* <u>Sports</u> Football Ice hockey Rugby	Control = 37 (20-50) Concussed = N/A	Retrospective Between participants	Dx: Self-report of physician 0 concussions 110/576 1 concussion 174/576 2-3 concussions 158/576 4-5 concussions 84/576 6+ concussions 50/576 Definition: Concussion in Sport Group (*ref 36)*	Subjective: Sleep disturbance questions of the 'PROMIS *In the past 7 days;* • *My sleep quality was…* • *My sleep was refreshing* • *I had a problem with my sleep* • *I had difficulty falling sleep* Rankings; very poor, poor, fair, good, very good. Sleep measures relative to most recent concussion – **NA** *All participants had retired 7 (±5) years ago.*	Compared to 0 concussion controls, odds ratios (95% confidence intervals) of reporting sleep disturbances per incidence of concussion (p-values not reported); 1 concussion = 1.8 (0.8 - 3.9) 2-3 concussions = 1.9 (1.0 - 3.6) 4-5 concussions = 2.0 (1.0 - 4.2) 6+ concussions = 5.2 (2.4 - 11.2) *Details/scored of questions not provided.*

Hoffman 2017 *(ref 43)*	Cohort (all concussion) = 151 (f = 66) <u>Sports</u> NA‡	Cohort = 19.3 (± 1.2)	Prospective (retrospective analysis of cohort) Within-participants	Dx: Physician Definition: Panel of Technical Experts (*ref 50*)	Subjective: self report changes in sleep duration (post-concussion total sleep time – baseline total sleep time)^^ Sleep measures relative to most recent concussion – within 2 days	81/151 reported longer sleep (2.2±1.5 hours) 35/151 reported no change in sleep (0.1±0.3) 35/151 reported shorter sleep (2.4±1.2) 'Short sleepers' indicated significantly more concussion symptoms within first 4 days after concussion compared to both no difference and long sleepers (p values not reported). No significant differences with the first 4 days existed between 'normal sleepers' and 'long sleepers'. Time to asymptomatic, and return to play, was not significantly different between any groups. *NB: 3+ concussions excluded from analysis*
Hoffman 2019 *(ref 44)*	Control = 20 (f = 12) Concussed = 20 (f = 12) <u>Sports</u> NA	Control = 20.4 (±1.4) Concussed = 20.0 (±1.5)	Prospective Between participants	Dx: physician Definition: Concussion in Sport Group (*ref 36)*	Objective – Actigraphy Subjective – Sleep diary (used as adjunct for actigraphy only), sleep quality (PSQI), daytime sleepiness (ESS), sleep symptom severity (SCAT3 – drowsiness + trouble falling asleep). Sleep measures relative to most recent concussion – <3 days	Compared to non-concussed participants; Concussed participants experienced significantly longer sleep onset latency (p=0.017) compared to healthy controls. Post-hoc indicated sleep onset latency at 2-3 days post-injury significantly longer in concussed group (p=0.002).

						Concussed participants demonstrated significantly increased variability of total sleep time (p = 0.044) and wake after sleep onset (p=0.017) compared to healthy controls. Concussed participants recorded significantly worse sleep quality (PSQI: 7.8±3.0 vs 4.2±1.8, p<0.001) and daytime sleepiness (12.6±5.3 vs 8.5±4.4, p<0.001). SCAT3 sleep symptom significantly higher in concussed (4.4±3.2 vs 0.8±1.4, p = 0.014) compared to healthy control.
Hutchinson 2017 *(ref 45)*	Control = 26 (f = 10) Concussed = 26 (f = 10) <u>Sport</u> Football Soccer Rugby Hockey Basketball Volleyball Lacrosse Baseball	Control = N/A (no significant difference to concussed) Concussed = 21.0 (±2.5)	Prospective Between participants	Dx: physician Definition: "*(1) observed or reported acceleration/deceleration of the head,* *(2) any observed alteration in mental status, and/or* *(3) signs such as confusion, vacant stare, poor coordination, difficulty concentrating, poor balance, and/or* *(4) any self reported symptoms such as headache, loss of consciousness, nausea, balance problems, or difficulty reading or concentrating.*"	Subjective: Sleepiness (SSS) Sleep measures relative to most recent concussion a) within 7 days (symptomatic) b) asymptomatic (days not reported) c) 7 days post return to play	Concussed significantly worse sleep symptoms (p values reported only as <0.05) during symptomatic phase compared to controls (*SSS scores not reported)* No differences in sleep during asymptomatic and post return to play.

Raikes 2016 *(ref 46)*	Control = 10 (f = 5) Concussed = 7 (f = 4) <u>Sports</u> NA	Control = 24.1 (± 1.9) Concussed = 22.7 (± 1.2)	Prospective Between participants	Dx: physician Definition: Concussion in Sport Group (*ref 36)*	Objective – actigraphy Sleep measures relative to most recent concussion – <4 days	No significant differences between concussed and non-concussed for total sleep time, sleep efficiency, and wake after sleep time ($p>0.05$ for all variables).
Vagnozzi 2008 *(ref 47)*	Cohort (all concussion) = 14 (f = 5) <u>Sports</u> NA	Concussed = 26.5 (20-35) (*NB individual ages reported, self-calculated)*	Prospective Observation	Dx: Self report Definition: "*A traumatically induced alteration in mental status, not necessarily with loss of consciousness*"	Subjective: Self-report sleep symptoms Sleep measures relative to most recent concussion – <3 days	4/14 reported sleep problem 2 reported trouble falling asleep 2 reported sleeping too long

Note: ref: reference. NA: Not available. ESS: Epworth Sleepiness Scale; PROMIS: Patient Reported Outcomes Measurement Information System; PSG: polysomnography; PSQI: Pittsburgh Sleep Quality Instrument; SCAT-3: Sport Concussion Assessment Tool, SSS: Stanford Sleepiness Scale.

^ The authors have been contacted to clarify the questions asked in this concussion assessment tool.

^^ In their manuscript, they describe *"Using the SCAT3, self-reported number of hours of sleep from the previous night was obtained as baseline and within 24-48 hours PI (post-injury)"*, however the SCAT3, nor any versions of the SCAT, measure self-reported sleep duration. Personal correspondence between primary authors clarified that sleep duration was measured in addition to questions asked during the symptom checklist of the SCAT.

‡ Data was from the Concussion, Assessment, Research and Education (CARE) consortium, which has recruited over 41,000 male and female National Collegiate Athletic Association athletes and service academy cadets.

6) Outcome/information; descriptive (e.g. means and standard deviations) and inferential statistics (e.g. *p* values)

Extracted data was synthesised in a standardised table (Table 1). As per scoping review guidelines, risk of bias and quality assessments were not undertaken.[29]

RESULTS

In total, 10 of 292 potentially relevant papers met study inclusion criteria, which resulted in 896 athletes who had experienced a SRC (involved in women's competition = 259).[38-47] Reasons for exclusion are outlined in the PRISMA diagram (Figure 1). Investigators of two studies were contacted for further information. Hoffman *et al.* explained how sleep duration was calculated for their study,[43] and Davis-Hayes *et al.* clarified the sleep specific question of the Concussion Resolution Index used in their study.[40]

Assessment of concussion

Physician diagnosis of SRC occurred in six studies.[39,40,43-46] Two studies utilised participant report of a physician diagnosis,[41,42] whilst the remaining two studies utilised self-report of SRC.[38,47]

The clinical definitions of concussion are outlined in Table 1. Five studies[39,40,42,43,46] utilised the definition created by the Concussion in Sport Group (who also create the SCAT questionnaire).[36] Two studies used definitions that were bought about by expert reviews of the literature. Participants from Hoffman *et al.*[43] were recruited as part of the Concussion Assessment, Research and Education (CARE) Consortium.[48] The CARE Consortium utilised the definition created by a Panel of Technical Experts.[49] Gosselin *et al.* [41] utilised the definition from the World Health Organisation 'Collaborating Centre for Traumatic Brain Injury'.[50] Two studies appear to use 'self' created definitions of concussion,[45,47] whilst the remaining study

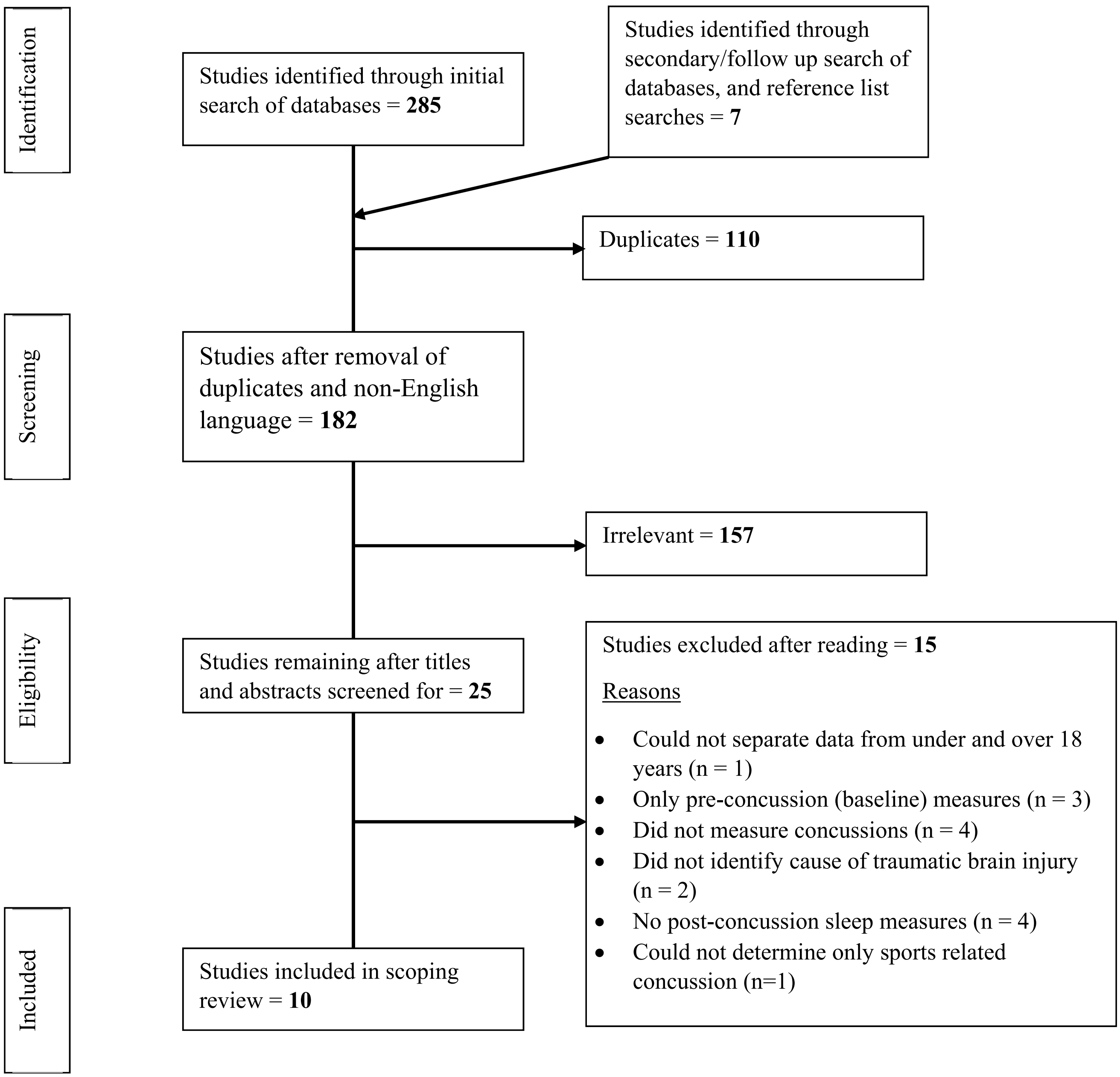

Figure 1. PRIMSA flow diagram of literature search and selection.

did not report the definition of concussion used,[38] only symptomology from the Rivermead Postconcussion Questionnaire.[51]

Assessment of sleep and/or sleep-related daytime dysfunction

Three studies utilised validated sleep questionnaires, with Gosselin *et al.* and Hoffman *et al.* administering the PSQI and the Epworth Sleepiness Scale (ESS),[41,44] whilst Hutchinson *et al.* utilised the Stanford Sleepiness Scale[45]. Three studies utilised individual sleep items from concussion screening tools, being the SCAT[39,44] and the Headminder Concussion Resolution Index[40]. Gouttebarge *et al.* examined sleep items from the Patient Reported Outcomes Measurement Information System (PROMIS), a patient health monitoring system.[42]

Three studies utilised non-validated and unstandardised questionnaires. Hoffman *et al.* examined perceived changes in sleep duration in the 48 hours post injury compared to before injury, as in more, less, or the same sleep duration.[43] Blake *et al.* and Vagnozzi *et al.* collected self-reported sleep disturbances, such as trouble initiating sleep or sleeping too long.[38,47]

Three studies utilised objective sleep measures. Two utilised actigraphy, [44,46] whilst the other utilised PSG.[41] Two of these studies also examined subjective measures using ESS and PSQI.[41,44]

Time between concussion and sleep assessment

Seven of the studies assessed sleep within a week of the study's participants sustaining a SRC,[39,40,43-47] with two of these studies undertaking longitudinal assessments of sleep.[43,45] One study examined sleep between one and eleven months after the participant's concussion,[41] whilst another examined sleep symptoms several years after retiring from sport, although did not mention when their participant's last concussion occurred.[42] Another study also did not report the time between their participant's sustaining a SRC and the sleep assessment.[38]

Associations of concussion and sleep

Overall, eight of the nine studies examining subjective sleep measures described some form of sleep disturbance occurring after SRC.[38,40-47] Two studies examined changes in sleep duration.[43,47] Hoffman *et al.* reported that half of their cohort who experienced SRC were sleeping for two hours longer than what they did prior to the concussion, whereas just under a quarter reported sleeping two hours less than what they did prior to concussion. The remaining participants reported no changes in sleep duration.[43] Vagnozzi *et al.* reported that four of 14 participants reported sleep disturbances, with two participants reporting trouble falling asleep, whilst the other two reported sleeping more than usual.[47] Two studies demonstrated those who experienced a SRC reported worse sleep quality, assessed by the PSQI, compared to non-concussed controls.[41,44]

Three studies examined daytime sleepiness. Two of these studies, one utilising the ESS and the other utilising the Stanford Sleepiness Scale, demonstrated those who experienced a SRC reported elevated levels of daytime sleepiness compared to non-concussed healthy controls.[44,45] In contrast, the remaining study, utilising the ESS, found no differences in sleepiness between those with SRC and non-concussed controls,[41] however data collection for this study occurred at least one-month after the last SRC, and they did report poorer subjective sleep quality in those who experienced a SRC.

Of the three studies which utilised sleep questions from a concussion assessment tool, two studies reported sleep disturbances,[40,44] whilst the other did not.[39] Churchill *et al.*, who showed no sleep disturbances after a SRC, combined from the SCAT questionnaire drowsiness, difficulty falling asleep and ‘fatigue’.[39] Fatigue, however, is not considered a sleep disturbance.[52] By contrast, Hoffman *et al.*, who also used the SCAT questionnaire, only combined the drowsiness and difficulty falling asleep.[44]

Studies using objective sleep data also reported conflicting results. Using actigraphy, Hoffman *et al.* found those with SRC experienced significantly longer sleep onset latency as well as greater variability in total sleep/wake time after sleep onset compared to healthy controls.[44] In contrast, Raikes *et al.* showed no differences in actigraphy derived sleep measures in seven participants with SRC compared to 10 healthy controls.[46] Likewise, Gosselin *et al.* showed no differences in PSG derived sleep measures, including total sleep time, sleep efficiency, and composition of sleep stages, between 11 participants with SRC and 10 healthy controls.[41]

Three studies examined relationships between concussion metrics and sleep disturbances. Hoffman *et al.* found those who reported reduced sleep after a concussion had significantly more concussion symptoms compared to those who reported more sleep or no changes to sleep.[43] Blake *et al.* reported a significant positive correlation between concussion symptomatology and sleep disturbances.[38] They also found that athletes who experienced three or more SRCs reported a significantly higher number of sleep disturbances compared to those with fewer than 3 SRCs, and non-concussed controls. Gouttebarge *et al.* showed athletes with a history of one to five SRCs over their career were approximately twice as likely, and those with six or more SRCs were five times more likely, to report sleep disturbances.[42] Furthermore, participants included in this study reported these sleep disturbances several years after sustaining the last concussion. Neither study, however, elaborated on the specifics of the sleep disturbances.

Whilst the majority of studies examined both male and female athletes, only Davis-Hayes *et al.* examined differences in self-reported sleep disturbances between genders after SRC.[40] Female athletes reported significantly higher percentage of sleep disturbances compared to males. The specific disturbances, however, were not examined.

DISCUSSION

This scoping review identified 10 papers, including three large scale cohort studies, which examined sleep disturbances after SRC in 896 adults. From a mixture of both subjective and objective assessments of sleep, eight studies concluded sleep disturbances are common after a SRC,[38,40-45,47] with seven of these studies assessing sleep within a week of concussion occurring. Such disturbances included poor sleep quality, excessive daytime sleepiness, and perceived changes in sleep duration, with both sleeping longer and sleeping less being reported. Other findings include an apparent dose-response relationship between the number of SRCs experienced and the severity of sleep disturbance symptomology,[38,42] a potentially long continuation of subjective sleep disturbances after the initial event,[41,42] and the possibility that females are more sensitive to sleep symptoms following a SRC.[40]

Despite a paucity of evidence, changes in sleep duration after a SRC suggest an association between increased sleep duration and improved outcomes. In the studies that examined perceived changes in sleep duration, there was mix of those reporting increased sleep, decreased sleep, and no change to sleep, compared to either non-concussed controls, or prior to concussion.[38,43,47] Furthermore, the two studies which objectively measured sleep by actigraphy both reported a large coefficient of variations of total sleep time compared to non-concussed controls. Whilst seemingly contradictory, the differences post-SRC sleep duration allows speculation that sleep is used to help reduce the histological problems of SRC. As previously discussed, concussions lead to the deposition of amyloid-β and τ-protein, which are responsible for propagating CTE.[19,20] The glymphatic system, most active during deep sleep, removes these proteins.[53] Studies in the acute phase of the moderate to severe TBI indicate increased deep sleep,[54,55] suggesting that this is a common outcome. Thus, in people who report sleeping longer than usual after a SRC, it is hypothesised the brain is trying to increase the amount of SWS to maximise the glymphatic drainage. Conversely, for those who report sleeping less than usual after a SRC, they may be susceptible to either a reduction and/or disruption to deep sleep, which may have the potential to contribute to the development of CTE in later life.

Even though the preliminary findings suggest that SRCs result in some form of sleep disturbances, the majority of studies utilised subjective measures of sleep, with only three studies utilising validated sleep or sleep-related daytime dysfunction questionnaires.[41,44,45] This is further confounded by the overall heterogeneity of the questionnaires used. The search strategy, as well as the inclusion and exclusion criteria for this scoping review was intentionally designed to maximise the number of potential papers that could be included, however, we concede this would have contributed to this methodological heterogeneity.

Three studies utilised sleep questions from concussion assessment tools,[39,40,44] which included the only study to show no differences in the prevalence of sleep disturbances between SRC participants and non-SRC controls. Concussion assessment tools have never been validated in determining sleep disturbances. This may explain why Churchill *et al.*, using the SCAT, combined fatigue along with drowsiness and trouble falling asleep to gauge sleep disturbances,[39] whereas Hoffman et al., only combined drowsiness and trouble falling asleep.[44] Fatigue is the state of lethargy bought about due to constant mental and/or physical exertion, and is distinctly different from sleep disturbances.[56] Whilst sleep interventions alleviate drowsiness, it has no impact on fatigue.[52] Furthermore, the SCAT, which was utilised in two studies,[39,44] only asks for “trouble falling asleep”. Thus, those sleeping more than normal, an apparent common outcome after a SRC,[43] are not captured, thereby potentially underreporting the prevalence of sleep disturbances.

Three studies examined sleep through 'probing' questions, rather than validated questionnaires.[38,43,47] As there were no objective measures of sleep to corroborate what was reported by the participants, the findings of these studies need be interpreted with caution.

Only one small study examined overnight PSG between those with SRC and non-concussed controls.[41] Despite SRC participants reporting significantly worse subjective sleep quality assessed by the PSQI, no differences in any of the sleep metrics measured by the PSG, such as sleep duration, objective sleep efficiency, and the composition of sleep stages, were shown. Nevertheless, testing occurred between one and eleven months after the last SRC, and had relatively few participants (n=10 for both groups), which makes interpretation of the results difficult. Other studies which compared overnight PSG in moderate to severe TBI in the acute phase to non-TBI populations have shown differences in PSG, namely increased slow wave sleep and increased awakenings from sleep.[54,55] Therefore, it is reasonable to speculate that future studies to examine overnight PSG in the acute phase of a SRC injury will demonstrate differences compared to non-SRC participants.

Clinical Implications

No studies in humans have examined interventions to improve sleep in those who have experienced SRC. Only one study has examined the feasibility of implementing such an intervention, but has yet to examine whether the intervention improves neural rehabilitation.[57] A study examining TBI in Sprague Dawley rats showed increasing SWS through both behavioural (sleep deprivation resulting in rebound SWS), and pharmacological means (the administration of sodium oxybate), resulted in a reduced concentration of amyloid precursor protein, and improved memory.[58] Therefore, we are cautiously optimistic that interventions designed to improve sleep may result in improved recovery from SRC.

Other factors known to affect sleep, such as mental health problems and medication usage, were poorly controlled in the studies included in this review. Three studies excluded participants that reported mental health problems,[41,44,46] whilst a further three studies collected data on the incidence of mental health problems, but no adjustments for these were made in the analyses.[42,43,45] Only one study excluded those who reported using medications known to affect sleep.[44] This is especially pertinent considering over 10% of athletes may be prescribed sedative/hypnotic medication,[59] and over 5% of athletes have been prescribed opioids.[60] Only two studies considered, and subsequently excluded, athletes who reported a previously diagnosed sleep disorder.[44,46] This is despite growing evidence indicating many athletes suffer from either insomnia-like symptoms, such as difficulty initiating and maintaining sleep, or from obstructive sleep apnoea (OSA), which results in nocturnal intermittent hypoxemia.[59,61] Notably, insomnia-like disturbances during the pre-season can increase the susceptibility of athletes to SRC during subsequent competition.[62] Additionally, both insomnia-like problems and OSA are both independently linked with increased levels of amyloid-β and τ-proteins.[63,64] Furthermore, the accumulation of amyloid-β and τ-proteins independently disrupts deep sleep,[65] thereby potentially creating a vicious cycle of sleep disturbance and accumulation of these proteins. Thus, screening athletes for sleep disorders may improve identification of those potentially at risk of sustaining, or experiencing poor recovery from, a SRC.

Finally, no study has examined the potential role of the apolipoprotein genotype ε4 (APOε4) allele in SRC and sleep. Whilst the APOε4 allele is associated with a reduced number of concussions,[66] those with the APOε4 allele experience a higher risk of τ-proteins and amyloid-β accumulation after head injury.[67,68] Unsurprisingly, the prevalence of the APOε4 allele in those diagnosed with CTE is higher than the population average.[69,70] Importantly, the APOε4 allele increases the prevalence of insomnia,[71] OSA,[72] and poor sleep quality.[73] It is possible that athletes who report reduced sleep after a SRC, as well as worse sleep quality long after their last SRC, may have the APOε4 allele. Screening athletes for the APOε4 allele may also facilitate the early identification of those potentially at risk of experiencing poor sleep after a SRC.

Clinical assessment of SRC is usually done with standardised SRC assessment tools such as the SCAT,[36] or computerised tools such as Cogstate or ImPact.[74,75] As previously discussed, these tools do not allow for proper assessment of sleep disturbances due to asking superficial questions such as grading of "drowsiness" and "having trouble falling asleep". In the light of a possible association between sleep and recovery from SRC, it is reasonable to recommend adding a question about sleeping more than usual in assessments of SRC. The lack of studies examining the effect of interventions improving sleep after a SRC means definite recommendations for clinical practice cannot be made. Nevertheless, given the beneficial effects of good sleep on health and cognitive function, it is appropriate to recommend that an initial positive finding on sleep disturbances is an indication for a more in-depth sleep assessment with validated subjective sleep assessment tools and/or a sleep diary. Prolonged sleep disturbance may warrant objective assessments with accelerometery and a sleep diary, or ultimately PSG.

A limitation of this review itself is limiting studies that presented data for adults, defined as being 18 years and older. This was decided upon due to the differences in sleep physiology and methods in measuring sleep in children/adolescents, however, this means that the effect of SRC on those under 18 years remains unclear. A potential limitation was only examining sports-related concussions. This means that concussions that were sustained during recreational activity, or accidents during daily life, may not have been included in the literature search. Nevertheless, the relatively robust findings of the included studies, as well as the findings of studies examining moderate to severe traumatic brain injury, it is likely that non-sports related concussions would also result in some form of sleep disturbance.

Conclusions

The findings of this emergent field of research examining the effect of SRC on sleep, indicate that sleep disturbances are prevalent in those who experience a SRC. Due to the lack of consensus of the findings, mainly due to the heterogeneity of the methods of the available studies, it is not possible to provide definitive clinical recommendations specifically related to concussion at this time. Nevertheless, given the role of sleep and the glymphatic system removing amyloid-β and τ-proteins, which are the proteins responsible for CTE, we recommend that sleep is closely monitored after a concussion. If a player who has recently experienced a SRC reports ongoing sleep disturbances and/or excessive daytime sleepiness, it may be necessary to refer the player to a sleep specialist for further clinical investigation and ongoing care. Importantly, more research is needed to properly elucidate the effect of SRC on sleep, so that research examining the efficacy of interventions to improve sleep can be undertaken.

All future studies should combine objective and validated subjective sleep assessments, obtain pre-season baseline sleep measures, and collect sleep data as soon after the SRC as feasibly possible to ensure that any acute changes in sleep is captured. Furthermore, we propose that screening for underlying mental health and clinical sleep disorders, usage of medication that will affect sleep, and even identifying those with a genetic predisposition to concussion and poor sleep via the APOε4 allele should also occur.

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