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ORIGINAL RESEARCH

Feasibility of at-Home Sleep Monitoring in Adolescents with and without Concussion

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Background: Poor sleep is associated with longer recovery following adolescent concussion, making the longitudinal assessment of sleep important for monitoring recovery and identifying sleep disruptions. An important consideration for successful monitoring of sleep following concussion is the feasibility and adherence of a given sleep monitoring tool when used in an at-home environment. Understanding the usability of different sleep monitoring tools is essential for determining their applicability for longitudinal assessment in an ecologically valid environment.

Purpose: The purpose of this study was to: (1) report on the adherence and feasibility of at-home sleep monitoring in adolescents following concussion, and (2) compare outcomes of subjective and wearable measures of sleep between adolescents with and without a concussion.

Patients and Methods: Participants included adolescents within 21 days of a concussion and uninjured controls that participated in four separate, prospective and longitudinal investigations of sleep following concussion. Sleep data was measured with: (1) Dreem Headband; (2) Philips Actiwatch; (3) Fitbit; and (4) subjective sleep diary. Sleep data was collected nightly, and adherence was defined as percentage of nights the participant used the sleep-monitoring tool over the study duration. Independent *t*-tests and effect sizes were calculated for the following sleep data outcomes as measured by each of the monitoring tools: duration, efficiency, latency, wake after sleep onset.

Results: Sleep data for a total of 183 adolescents (104 with concussion, 79 uninjured controls) was assessed. Adherence rates across all devices ranged from 53% to 98%, with the subjective sleep diary showing the highest adherence rate for both groups (concussion: 91%, control: 94%). Across the four different monitoring tools, adolescents with a concussion demonstrated longer duration, latency, wake after sleep onset, and lower (worse) efficiency, with medium to large effect sizes.

Conclusion: The results indicate that at-home sleep monitoring is a feasible approach for tracking sleep in adolescents following concussion.

Keywords: sleep assessment, concussion, adolescent

Introduction

An individual's sleep health is characterized by their sleep duration, efficiency, timing, alertness, and overall quality.[1] Sleep health plays a fundamental role in concussion recovery, particularly among adolescent athletes.[2–7] In the first 3 weeks following concussion, adolescents with self-reported sleep symptoms (eg, difficulty falling or staying asleep) demonstrated a nearly fourfold increase in recovery time.[2] Similarly, adolescents with concussion have demonstrated shorter sleep duration and diminished sleep efficiency, and greater time awake after onset of sleep than uninjured controls for up to one year after injury.[3] Alongside other studies,[4,6,8,9] these findings indicate that concussion recovery may be influenced by complex physiological changes underlying sleep regulation.[10] The assessment of post-concussion sleep health may provide valuable clinical insights to facilitate recovery, but poses unique challenges. Changes in sleep health following concussion can be subtle, multidimensional, and vary in severity and timing.[3–8,11,12] Difficulties with sleep health generally refer to any combination of acute or chronic problems with maintaining and/or regulating sleep (eg,

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insomnia or delayed sleep onset). To effectively manage these changes in adolescents with concussion, the applicability and feasibility of different assessment strategies must be evaluated.

Sleep is a broad topic and of interest across many fields of science, and as such many measurement tools exist to quantify a variety of different outcome variables. Polysomnography (PSG) is considered the gold standard for sleep assessment.[13] PSG is often performed during an overnight stay in a sleep laboratory and requires trained personnel to set up, monitor, and interpret the study. It yields extensive data regarding the physiological sleep domains (eg, sleep staging, respiratory rate, oxygen saturation). However, the high financial and logistical requirements make it impractical for evaluating habitual sleep over multiple nights or in the home environment. Given the inherent limitations of PSG, other tools exist for sleep monitoring including sensor-based devices, subjective sleep questionnaires, and sleep diaries.

Progress in technology has given rise to the development of sensor-based devices (ie, wearables) that allow for longitudinal and portable measurement of sleep within a participant's own sleep environment, and with them, increased amounts of data regarding an individual's habitual sleep. These wearable devices can be classified as medical grade (eg, Philips Respironics Actiwatch) or consumer grade (eg, Fitbit). However, sensor-based devices are not as accurate as PSG because their estimates of sleep are based on patterns of movement.[14] Daily questionnaires assessing sleep are subjective and highly variable due to their reliance on perception and memory of sleep experiences over a time period (eg, 1 week, 1 month).[15] Yet, despite these limitations, subjective questionnaires may be more practical to gather longitudinal data than other approaches. While questionnaires encapsulate a designated period of time retrospectively, daily sleep diaries may be beneficial for capturing nightly variations in sleep in real time, particularly following a concussion.[15] Sleep diaries can prospectively monitor sleep for factors that may interfere with good quality sleep, such as bed and wake times, length and number of daytime naps.[16] While PSG is considered the gold standard for measuring sleep, questionnaires or wearables are most often used within concussion research and sports medicine clinical settings due to their ability to measure habitual sleep, as opposed to one night (as measured via PSG). As such, leveraging technology and subjective reporting for at-home sleep monitoring may offer unique insights into an individual's sleep health.

Given the diverse range of tools that clinicians and researchers can use, selected measurement tools should align with the aspect of sleep health being assessed. Specifically, following concussion, the common outcomes of sleep health assessed include:[2–6,11,17,18]

- Sleep duration: *Total time asleep*
- Sleep efficiency: *Percent of time asleep/total time in bed*
- Sleep onset latency: *Time taken to initially fall asleep*
- Wake after sleep onset (WASO): *Time awake in each sleep episode after onset latency*
- Subjective sleep quality: *Overall satisfaction with sleep*

While different sleep measurement devices may assess the same sleep health outcomes (eg, duration, efficiency, latency), the resulting data may vary significantly depending on the technology and algorithms used. This variability can introduce challenges in interpreting sleep data, particularly when comparing results across different devices or studies. For clinicians, understanding these discrepancies is essential, as it influences clinical decision-making regarding sleep health and optimal treatment pathways. Despite the increasingly large amount of research supporting sleep as a modifier of recovery from concussion, we have an incomplete understanding of the feasibility of measuring habitual sleep in the home environment, particularly among adolescent athletes. Collegiate and professional sports provide financial resources and access to skilled personnel that are not typically available in adolescent and youth sports. Understanding the feasibility of at-home sleep monitoring using various sleep measurement tools and methods may provide clinicians and researchers the ability to make informed, evidence-based decisions for measuring sleep after concussion.

The purpose of this secondary data analysis was to evaluate a variety of sleep outcomes in an ecologically valid setting (at home) using both objective and subjective measures of sleep to: (1) determine the feasibility of various assessment tools for longitudinal at-home sleep monitoring among adolescents with and without concussion, and (2) compare outcomes of subjective and wearable measures of sleep between adolescents with and without a concussion.

This comparison of at-home sleep assessment methods allows for the quantification of applicability in the environments they are most often used.

Methods

Participants

We conducted a secondary analysis of four separate, prospective and longitudinal investigations of adolescent athletes between 2018 and 2023. For all studies, participants included adolescent athletes who had recently sustained a concussion (≤21 days) and uninjured controls. Participants in the concussion group were recruited from patients receiving treatment at a sports medicine center within a regional children's hospital. Concussion diagnosis was made by a sports medicine physician based on the definition of the most recent international concussion consensus guidelines available at the time of the study.[19,20] For the concussion group, participants reported an initial symptom severity score ≥ 9 as measured via Post Concussion Symptom Inventory,[21] were 13–18 years of age at the time of the initial evaluation, and able to participate in the post-concussion assessment within 21 days of injury. Uninjured control participants were recruited through the local community (ie, local high school and/or club athletes), and participated in an organized sport, had not sustained a concussion in the previous 6 months, and did not report any other co-existing neurological conditions. This study was reviewed and approved by the Colorado Multiple institutional review board (IRB) prior to commencement and complies with the Declaration of Helsinki. Participants and a parent/guardian for participants younger than 18 years of age provided written informed consent/assent prior to study participation.

Procedure

A feasibility study was implemented to determine practicality and implementation of at-home sleep monitoring.[22] The source participants were drawn from four separate studies, each measuring sleep with a different tool for a different length of time (Table 1). The measurement tools included the Dreem Headband, Philips Actiwatch, Fitbit, and a subjective sleep diary, all of which are explained in detail below. The sleep outcomes of interest were duration, wake after sleep onset (WASO), latency, and efficiency, as these are the most often reported outcomes in concussion literature. Of note, the specific outcomes captured by each tool is outlined below, as not all measurement tools captured all four outcomes.

Sleep Measurement Tools

Dreem Headband: Participants were provided with a research-grade Dreem 2 headband (Formerly: Dreem Labs, now: Beacon Biosignals) and given written and verbal instructions for how to use the device. Participants were instructed to wear the Dreem 2 headband for the first 2 nights and last 2 nights of a 14-day study monitoring period, as these timepoints coincided with separate outcomes being collected as part of that study protocol. When fully charged, the

Table 1 Feasibility Outcomes Based on Sleep Monitoring Tool and Number of Participants in Each Group with Accompanying Data

Sleep Monitoring Tool	Method of data collection	Frequency	Length of monitoring (days)	Participants (N)
Sleep diary	Web-based, via REDCap	Daily	21	Concussion (8) Control (20)
Fitbit	Wrist-worn accelerometer	Nightly	28	Concussion (96) Control (58)
Philips Actiwatch	Wrist-worn actigraphy	Nightly	21	Concussion (6) Control (20)
Dreem EEG headband	Portable EEG	Nightly	4 (over a 2 week period)	Concussion (5) Control (20)

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Dreem 2 headband could be used for approximately 12 hours before additional charging was needed. The Dreem 2 headband is wireless and contains three types of sensors that record five types of physiological signals: (1) brain cortical activity measured via five electroencephalogram (EEG) dry electrodes (3 across the frontal band, and 2 in the suboccipital region); (2–4) body movements and position, and breathing rate via a 3D accelerometer located over the top of the head; (5) heart rate via a red-infrared pulse oximeter.[23,24] The Dreem recordings were manually started and stopped by participants via the Dreem app each night/morning. Sleep outcome measures derived from Dreem were: duration, WASO, latency, and efficiency. The calculation of these outcome measures is unknown due to Dreem's proprietary algorithm.

Actiwatch: The Philips Actiwatch Spectrum Plus (Philips Respironics, IC.; Bend OR, USA) is a research-grade actigraphy device worn on the wrist and has been previously used among adolescents following brain injury.[25] The Actiwatch Spectrum Plus can be worn continuously for approximately 50 days before additional charging is needed.[26] Participants were instructed to wear the Actiwatch nightly throughout the 14-day monitoring period. Rest periods were set manually by study staff using daily sleep diaries. Actiwatch sleep and wake data were analyzed in 1-minute epochs using the medium sensitivity threshold with the Actiware software package (version 6.0; Philips Respironics, Inc.; Pittsburgh, PA, USA). Sleep outcome measures derived from the Actiwatch and automatically calculated by Actiware software were: Duration (the total number of epochs for a given rest interval scored as sleep by Actiware multiplied by the epoch length in minutes); Sleep Efficiency (total sleep time divided by time in bed multiplied by 100), WASO (the total number of epochs between the start time and end time of the given sleep interval scored as wake by Actiware software multiplied by the epoch length in minutes), and sleep latency (the time between the start of a given rest interval and the sleep interval start time and is controlled by the sleep interval detection algorithm).

Fitbit Charge: Participants were provided a Fitbit Charge 2 (Fitbit Inc, San Francisco, CA, USA) and instructed to wear it on their non-dominant wrist, daily and nightly for the duration of their monitoring period (approximately 28 days). The Fitbit Charge can be used for approximately 4–5 days before additional charging is needed, and is highly accurate in recording sleep parameters.[27] Sleep outcome measures derived from the Fitbit included duration, efficiency, and WASO. The calculation of these outcome measures is unknown due to Fitbit's proprietary algorithm.

Daily sleep diary: Participants were instructed to complete daily sleep diaries via online webform Research Electronic Data Capture (REDCap)[28] shortly after getting out of bed in the morning, for the length of participation in the study (approximately 21 days). Daily sleep diaries were sent every morning via text message or Email with a link to the online webform and took approximately 2 minutes to complete. Sleep diaries are considered reliable measures compared to PSG and are common practice to use for verifying actigraphy data (Philips Actiwatch).[15,29,30] The sleep diary outcome measures included: sleep duration (self-reported hours), sleep latency (self reported time taken to fall asleep), and WASO (self-reported sum of minutes awake during sleep episode).

Statistical Analysis

Descriptive statistics (means, standard deviations, percentages) and inferential statistics (independent sample t-tests, Cohen's d effect sizes) were calculated for participants across the 4 studies to compare demographic and sleep outcome variables between concussion and control groups. Due to unequal and small sample sizes for the Actiwatch, Dreem Headband, and sleep diaries, Cohen's-d effect sizes were calculated for all measurements. Effect size was interpreted as follows: small = 0.20; medium = 0.5; large $\geq$ 0.8.[31] Feasibility outcomes were based on data related to recruitment and adherence. (Table 1) Measurement tool adherence was calculated as the number of participants who completed the sleep task for each day of the study period (eg, wore the device, filled out the sleep diary) divided by the total number of participants in that study.

The primary sleep outcome measures were sleep duration, sleep onset latency, sleep efficiency, and WASO. Statistical analyses were performed using R Studio (version 4.2.2, R Core Team 2022, Vienna, Austria).

Results

Adolescents with and without concussion were similar in most demographic variables, except for race (Table 2), where there was a higher proportion of white participants in the control group relative to the concussion group. The average

Table 2 Participant Demographics Stratified by Group

	Concussion (N=104)	Control (N=79)	P-value
Age (years)			
Mean (SD)	15.4±1.7	15.4±1.5	0.83
Biological Sex			
Male	58(55%)	45(57%)	0.88
Female	46(45%)	34(43%)	
Race			
Asian or Asian American	6(6%)	0(0%)	0.01
Biracial	13(12%)	7(9%)	
Black or African American	4(4%)	0(0%)	
Hispanic or Latino	5(5%)	0(0%)	
Not Reported	7(7%)	5(6%)	
White	70(67%)	67(85%)	
Time since concussion (days)			
Mean (SD)	9.6±4.1		
Days to Asymptomatic			
Mean(SD)	33.8± 26.8		

length of sleep monitoring was 20.3±21.8 days. For adolescents with a concussion, the average time from injury to study enrollment was 9.6±4.1 days, and the average time to symptom resolution was 33.8± 26.8 days.

Adherence rates were lower among adolescents with concussion compared to those without a concussion for all monitoring tools assessed (Figure 1). The means and standard deviations of adherence rates are as follows: Dreem Headband: 0.94±0.16

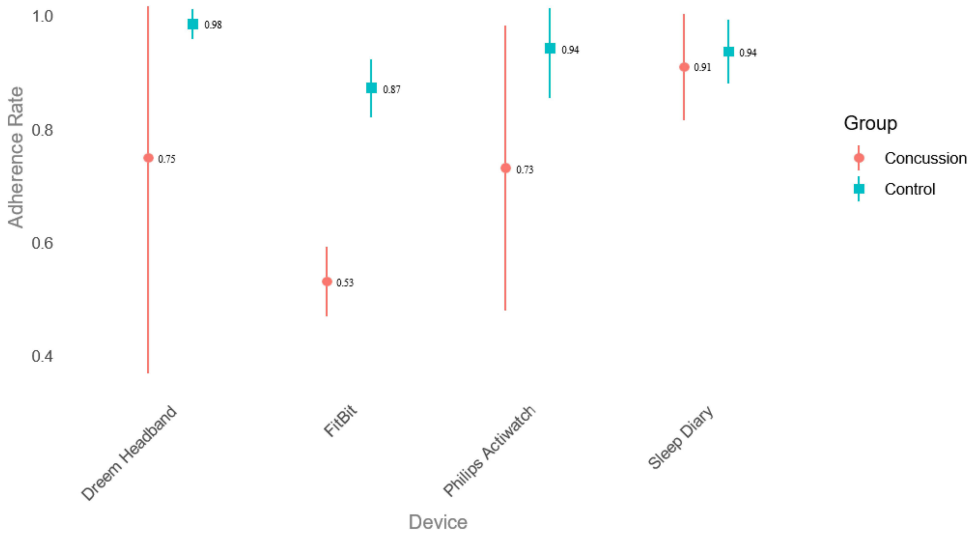

Figure 1 Average adherence rates for length of study participating for sleep monitoring tools, stratified by group.

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Table 3 Mean Sleep Outcomes for Each Sleep Monitoring Tool, Stratified by Group. Due to Unequal and Small Sample Sizes for the Actiwatch, Dreem Headband, and Sleep Diaries, Cohen's-d Effect Sizes Were Calculated for All Measurements.

	Concussed	Control	P-value	Effect Size
Sleep Duration (minutes)				
Actiwatch	544.2±56.0	491.9±47.9		−1.02 (−1.98—0.04)
FitBit	431.9±48.2	441.4±32.2	0.19	0.22 (−0.11–0.55)
Dreem Headband	473.5±45.1	443.7±54.1		−0.57 (−1.55–0.43)
Sleep Diary	554.6±47.6	498.5±37.6		−1.38 (−2.27—0.47)
WASO (minutes)				
Actiwatch	70.4±28.3	56.1±15.0		−0.7 (−1.64–0.26)
FitBit	63.4±11.1	62.6±9.7	0.68	−0.07 (−0.4–0.26)
Dreem Headband	15.9±3.7	24.4±16.6		0.57 (−0.43–1.55)
Sleep Diary	14.4±14.3	7.9±7.8		−0.65 (−1.53–0.23)
Latency (minutes)				
Actiwatch	14.6±12.6	4.7±2.7		−1.45 (−2.45—0.42)
Dreem Headband	26.1±18.2	17.9±16.0		−0.5 (−1.48–0.5)
Sleep Diary	18.1±6.3	14.2±8.4		−0.50 (−1.33–0.34)
Efficiency (%)				
Actiwatch	83.6±4.6	86.9±2.7		0.97 (−0.01–1.92)
FitBit	87.8±2.0	88.7±2.4	0.03*	0.47 (0.14–0.80)
Dreem Headband	91.0±3.4	91.5±5.1		0.1 (−0.88–1.08)

Note: *P<0.05

(concussion: 0.75±0.27, control:0.98±0.05), Fitbit: 0.72±0.30 (concussion: 0.53±0.30, control: 0.87±0.19), Philips Actiwatch:0.90±0.18 (concussion:0.73±0.14, control:0.94±0.18), sleep diary: 0.93±0.11 (concussion:0.91±0.11, control: 0.94±0.11).

A secondary aim of the study was to identify differences in sleep health outcomes between adolescents with and without concussion. Mean values for each sleep outcome based on measurement tool can be found in Table 3. The Actiwatch demonstrated longer sleep duration, WASO, latency, and efficiency for the concussion group with large effect sizes. Conversely, the sleep diary and Dreem Headband demonstrated medium effect sizes for their respective sleep outcomes (Table 3). Independent t-tests for the Fitbit demonstrated significantly worse sleep efficiency in the concussion group compared to controls (87.8±2.0 vs 88.7±2.4, p=0.03), with a medium effect size. No significant differences were found between groups for sleep duration or WASO as measured by Fitbit (Table 3) Radar plots depicting sleep outcomes by device can be found in Figure 2. For each radar plot, the outer edges correspond to higher values for the given metric. Higher values for sleep duration and efficiency indicate better sleep, whereas higher values for latency and wake after sleep onset indicate poorer sleep.

Discussion

This study reports the feasibility and adherence of using four different sleep assessment tools for at-home monitoring following adolescent concussion and their associated measurement outcomes of sleep health. As measured by medium to

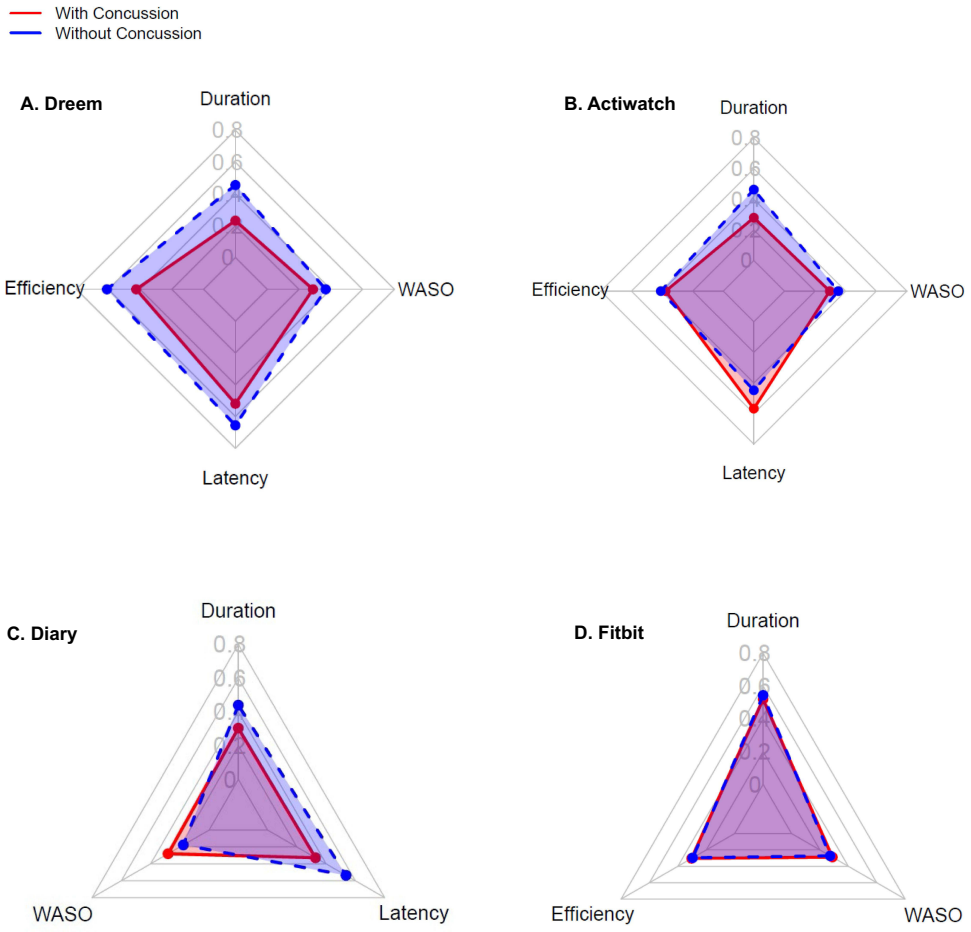

Figure 2 Radar plots comparing sleep outcomes for Dreem headband A, Philips Actiwatch B, sleep diary C, and Fitbit D, between adolescents with (red) and without a concussion (blue). The outer edges correspond to higher values for the given metric. Higher values for sleep duration and efficiency indicate better sleep, whereas higher values for latency and wake after sleep onset indicate poorer sleep.

large effect sizes, adolescents with a concussion demonstrated longer sleep duration, WASO, latency, and efficiency using Actiwatch, Dreem, and sleep diary measurement tools. Fitbit results indicated small effect sizes for sleep duration and WASO, but significantly lower sleep efficiency with a medium effect for those with a concussion, relative to controls. Although these differences are consistent with previous studies among adolescents,[3–8,12] this study addresses the feasibility of obtaining these results. The results of our study highlight that although differences in sleep may exist between those with and without a concussion, there is significant variability in the feasibility and adherence, as well as domains in which we observed differences, across measurement devices and approaches. Our results suggest that it may be advantageous to use both subjective and objective measures of sleep, depending on the sleep outcome of interest and desired adherence.

Changes in sleep throughout concussion recovery have been studied in adolescent populations.[3–8,32] Subjective sleep changes include poor sleep quality, worse sleep duration and efficiency, and greater wake after sleep onset.[3,4,6,11,12,33] The results of our study were similar, with general findings of less efficiency and increased sleep duration, WASO, and latency in those with a concussion compared to controls. Objective changes in sleep previously reported following concussion have included longer sleep onset latency, decreased efficiency, and both increased and decreased amount of total sleep time.[3,4,32] However, previous research has reported conflicting findings between objective sleep changes measured via actigraphy or commercial wearable devices and subjective sleep measures. In particular, individuals with a concussion have demonstrated significant differences in subjective measures of sleep, but not in objective measures.[33,34] The results of our study coincide with these previously reported discrepancies. For example, we observed

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a large effect size for longer sleep latency in those with a concussion compared to uninjured controls using Philips Actiwatch, but only moderate effect sizes when measured by Dreem or sleep diary. Similarly, sleep duration was greater in those with a concussion when measured via sleep diary and Philips Actiwatch (Cohen's $d > 1.0$), but small effects were observed when measured with Fitbit or Dreem (Cohen's $d < 0.6$). Though subjective assessment of sleep is valuable for understanding how perceived quality of sleep is affected by concussion, our results and previous research[11,33] suggest that self-reported sleep measures may not coincide with objective measures. As such, a combination of subjective and objective methods may complement each other and provide a more robust assessment.

The discrepancy between adolescent sleep recommendations and the actual sleep habits of adolescents has been previously highlighted in research.[35] The national Sleep Foundation recommends that adolescents achieve 8–10 hours of total sleep time each night, sleep latency of 0–30 minutes, and sleep efficiency >85%. Our study observed that adolescents with concussion demonstrated a mean of 7.2 and 7.8 hours of sleep per night as measured by the Fitbit and Dreem devices, respectively, further adding to the discrepancy between recommendations and sleep habits. Similarly, uninjured controls demonstrated fewer hours of sleep than recommended (7.3 hours and 7.9 hours via Fitbit and Dreem, respectively). This is important because sleep is a key element in concussion recovery and may influence functional assessment for return to sport. Sufrinko et al, showed differences in pre-injury neurocognitive performance in uninjured athletes that self-reported a night sleep restriction (≤5 hours) compared to those that obtained an optimal night of sleep (≥ 9 hours).[36] Those that obtained less than 5 hours of sleep performed worse on measures of verbal and visual memory, visual motor speed, and reaction time, suggesting cognitive performance is influenced by sleep.[36] Similarly, following adolescent concussion, sleeping less than 7 hours the night before neurocognitive testing was associated with higher symptom reporting, whereas sleeping greater than 9 hours was associated with worse neurocognitive performance.[8] However, it should be noted that these studies examined only a single night of sleep, making it unclear as to whether sleep outcomes collected were truly representative of a typical night's sleep, further emphasizing the importance of longitudinal at-home sleep monitoring.

Although sleep outcomes across the measurement tools were generally worse in the concussion group, the conclusions that can be drawn are ambiguous as the sample size varied between groups and devices used. The Fitbit had the largest and most equal sample size between groups. However, it also had the lowest adherence rates among adolescents with concussion, and only sleep efficiency was significantly different relative to controls using this method. Moreover, sleep duration demonstrated no significant differences and small effect sizes. Though this is similar to previous research[4] the lack of significant difference between groups seen in our results gives caution to their clinical applicability.

Methodological Implications

Importance of Device Selection

As discussed, sleep monitoring tools measure numerous aspects of sleep health, and the outcome of interest should be taken into consideration when choosing which tool to use. Though each sleep outcome can be viewed alone, a multidimensional understanding of sleep health requires several elements to understand sources of sleep disruption, particularly given that poor sleep quality is one of the most commonly reported complaints following a concussion.[2–8,11,12,37] The National Sleep Foundation recommends that when assessing sleep quality, the outcomes most optimal for consideration include latency, WASO, number of awakenings that are greater than five minutes, and sleep efficiency.[38] In our study, participants with a concussion generally demonstrated worse sleep efficiency. Though important, sleep efficiency does not capture episodes of wakefulness throughout the night, and as such, latency and WASO should be examined in tandem. Similarly, when using a sleep diary, calculation of total sleep duration is contingent upon subjective recall of an individual's WASO and sleep latency, as these are subtracted from the total time in bed to determine duration. As such, estimates of sleep duration are likely overestimated compared to objective measures.

Technological Advancements and Limitations

Progress in technology has given way to devices that allow for more objective sleep measurement and more information regarding sleep habits. This has been beneficial to clinicians and researchers alike for several reasons. Wearables such as Fitbit or Actiwatch allow for continuous monitoring of sleep with minimal patient burden. The continuous data collected

allows clinicians to better understand sources of sleep disruption on an individualized basis, leading to more precise intervention strategies. While progress in sleep monitoring technology is beneficial, there are inherent limitations such as poor adherence or cross device variability, as highlighted by the results of our study. Though the sleep outcomes measured were the same across each device, the data yielded varying results. If relying on a singular device, there may be incomplete or inaccurate sleep health information obtained. One potential reason for this is that actigraphy monitors are prone to differences based on the model of the device as well as the algorithm/software used to determine sleep outcomes. As such, these monitoring tools tend to under estimate total sleep duration and over estimate awake time. For this reason, use of both an objective and subjective monitoring tool may complement each other, providing more robust data to guide clinical care.

Adherence

Poor adherence rates across devices also pose a challenge in obtaining complete sleep health information. We found that adherence rates varied significantly across monitoring tools, highlighting an important aspect of feasibility. The Dreem headband had a 75% adherence rate amongst those with concussion, which was lower than those without a concussion (98%). One factor contributing to this poor adherence rate was comfort level. Participants who were experiencing concussion symptoms may have found wearing a device around their head to further exacerbate their symptoms during sleep and removed it, leading to incomplete or poor-quality data. Of all the monitoring tools, Fitbit had the lowest adherence amongst those with a concussion (53%). This raises significant concerns about its practicality, as lack of consistency in wearing the device may result in insufficient data that can be used for clinical decision making. When using either of these devices, written/verbal instructions should be provided, and ongoing troubleshooting should occur with participants during the monitoring period. Despite being the least technologically advanced monitoring tool, the sleep diary had the highest adherence rates, potentially due to simplicity and ease of use. Though our results demonstrated varying adherence rates, this challenge is not uncommon when monitoring sleep. In adolescents, Sinclair et al, previously reported having to exclude 28% of their enrolled participants from final analysis due to nonadherence with actigraphy procedures.[39]

Accessibility to Data/Data Analysis

Consideration should be given to availability, storage, and useability of each device. With respect to the devices we used, all three have software for required data storage and analysis. The Dreem headband allows for a maximum of 100 hours of data storage per device before overwriting, making it crucial to upload to the cloud-based software within the respective time.[40] Finally, data quality varies across all devices. Specific to the Actiwatch, manual scoring is required to determine the period of analysis each night and requires a trained individual. Data useability for the Dreem is based on the device's record quality index score, which shows what percentage of the night's data is still scoreable on at least one channel during one recording. According to the Dreem software, the record quality index must be at least 70% to provide usable data. However, the average quality index score for individuals with a concussion in our study was 66%, thus limiting the useability of the data.

Limitations

A primary aim of this study was to determine feasibility of at-home monitoring of sleep following adolescent concussion. This methodological design naturally impacted data quality and adherence, as well as sample size. As a result, a limitation is that statistical conclusions could only be drawn from one (Fitbit) of the four sleep-monitoring methods. Additionally, effect sizes for Dreem, Actiwatch, and Sleep Diary may be subject to potential bias due to unequal sample sizes. Future research should address performing a validation study of the different measurement devices with each other to determine relative accuracy in adolescents with and without a concussion. Finally, at the time of study completion, Philips Actiware had been discontinued, limiting the usability of the Actiwatch for future studies.

Conclusion

Negative changes in sleep are commonly reported by adolescents following concussion and has been implicated as a key recovery factor. To effectively manage these changes in adolescents with concussion, the applicability and feasibility of different assessment strategies must be considered. Both subjective and objective methods for measuring sleep in adolescents with concussion comes with varying advantages and disadvantages. Understanding the limitations of approaches such as actigraphy, wearables, or subjective sleep diaries is essential for accurate data interpretation and clinical application. The data acquired in this investigation support that sleep can be monitored in an ecologically valid environment following concussion in adolescents. Each approach provides potential avenues for future research, and elements such as adherence, usability, and participant guidance should be considered. Improving how sleep is measured following concussion can strengthen the understanding of the link between sleep and concussion as well as improve monitoring in future studies.

Abbreviations

EEG, Electroencephalogram; PSG, Polysomnography; REDCap, Research electronic data capture; WASO, Wake after sleep onset.

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