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Original Article

Comparing measures of free-living sleep in school-aged children

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ABSTRACT

Objective/Background: Recent technological advances and emerging commercially-available consumer-friendly sleep assessment products affords researchers with a host of tools to consider for capturing free-living sleep in children. The purpose of this study was to compare free-living sleep characteristics (duration and bed/wake times) across different measures in children.

Methods: Elementary school-aged children (N = 30, mean age 7.2 years, 63% boys, 87% non-Hispanic white) wore an ActiGraph GT9X Link© and Fitbit Charge HR© on the non-dominant wrist, with a Beddit 3 Sleep Monitor© affixed to their mattress for two consecutive weekend nights of free-living sleep. Parents completed a sleep log of bed and wake times. Absolute differences in bed and wake times were examined and Bland Altman plots assessed the level of agreement across sleep measures.

Results: Across the four sleep measures, total sleep time (TST) ranged from 458 min/night (ActiGraph GT9X Link©) to 613 min/night (Parent report). Mean bed and wake times ranged from 8:46$_{PM}$ to 9:03$_{PM}$, and 6:52$_{AM}$ to 7:16$_{AM}$, respectively. Pearson correlation coefficients were moderate between all four sleep measures (range r = 0.30–0.71). Bland–Altman plots indicated the highest level of agreement for TST was between Beddit 3 Sleep Monitor© and Fitbit Charge HR© (mean difference −11.7, limits of agreement: 119.0, −142.4 min).

Conclusions: The findings from this study show a high level of agreement of when a child goes to sleep and wakes up across a variety of sleep measures; however, more work is needed to classify TST once the sleep period has commenced.

1. Introduction

Children's sleep has been identified as a critical marker of health and well-being [1]. Considerable evidence over the last two decades shows an association between sleep duration and non-communicable diseases in children such as hypertension, diabetes, and a higher prevalence of overweight and obesity [2]. Therefore, the assessment and ability to capture children's sleep has become of paramount importance. Sleep is a complex and multi-faceted behavior and requires researchers to choose from a host of measurement options (eg, daily sleep logs, actigraphy, polysomnography [PSG]), and outcomes (eg, quantity, quality, timing). PSG is considered the “gold standard” for providing detailed information about all sleep outcomes however, it is expensive, obtrusive, and is best conducted in a laboratory setting [3]. Thus, it is difficult to assess sleep in large cohorts and problematic for researchers looking to assess sleep in free-living conditions [4]. Given these methodological constraints, less obtrusive and expensive sleep measurement devices have been developed, such as actigraphy. Actigraphy measures human rest/activity cycles through wrist-worn devices that capture 24-hour movement and translates that movement to sleep-wake scores based on scoring algorithms [5]. Given the low-burden of actigraphy, it has become the most popular method of capturing and assessing sleep, overtaking PSG in the last 20 years [1,4–6]. Yet, the actigraphy field still lacks established standards and scoring protocols for pediatric sleep measurement [7].

Recent technological advances and the emergence of commercially-available consumer-friendly sleep assessment products affords researchers with a host of new tools to consider for capturing free-living sleep in children [3]. For example, the Beddit 3

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Sleep Monitor© from Apple Inc. incorporates ballistocardiography (BCG)-based assessments (ie, heart and breathing rate) in combination with quantified movement data to establish sleep outcomes [8]. In addition, wearable-tech companies such as Fitbit© offer an array of aesthetic, wrist-worn fitness trackers that include sleep assessment capabilities and provide an attractive alternative to scientific-grade devices.

Studies have validated and compared sleep outcomes between commercially-available wrist-worn devices and PSG or actigraphy; however, the majority of these studies have taken place in lab-based settings/conditions and have focused on adolescents, young adults, or clinical populations [6,8–12]. There is a lack of evidence directly comparing children's free-living sleep outcomes across different measures [9,13]. The purpose of this study was to compare free-living sleep estimates (duration and bed/wake times) across different sleep measures in a sample of elementary school-aged children.

2. Methods

2.1. Participants

A convenience sample of 30 apparently healthy children (mean age: 7.2 ± 2.1 years, 63% boys, 87% non-Hispanic white) were recruited from a school district in South Carolina to be part of this study. Prior to data collection, all study procedures were approved by the Institutional Review Board of the lead authors' institution and written informed consent and child assent were obtained. Participants/families received a reimbursement of $25 for participation in the study.

2.2. Protocol

All study procedures occurred in the child's natural sleep environment (ie, at home) over two-consecutive nights (Friday and Saturday) in the fall (2017) and spring (2018). Trained research assistants contacted the families to arrange a suitable time to arrive at the child's home (Friday afternoon) and setup/distribute the data collection materials. During setup at the child's home, the research assistant scheduled a time with the parent/guardian to return to collect the materials 48 h later (Sunday afternoon). For two consecutive nights, children wore two different devices on their non-dominant wrist, had a sleep detection device affixed to their bed, and parents completed a daily diary. A description of each sleep measure is outlined below.

The Beddit 3 Sleep Monitor© (Apple Inc., Cupertino, CA, USA) is a ballistocardiograph-based device that collects information, such as heart rate, breathing rate, and musculoskeletal movement. Ballistocardiography is commonly used in clinical research to measure vital signs and/or sleep [8]. The Beddit 3 Sleep Monitor© is 31.5-inch long x 3.1-inch wide x 0.06-inch high detection strip that lies above the mattress and underneath the bedsheet. It has considerable promise as a free-living sleep analysis tool as it does not interfere with normal sleeping habits [8]. Under parent supervision, research assistants affixed the Beddit 3 Sleep Monitor© to the child's bed, set up an Apple iPad© and logged in to the Beddit 3 Sleep Monitor© app to record sleep metrics continuously for 48 h.

The Fitbit Charge HR© (Fitbit Inc., San Francisco, CA, USA) is a commercially available wireless activity-tracking wristband. The Fitbit Charge HR© generates estimates of activity (eg, calories burned, minutes of activity at different intensities, steps) and sleep (eg, time to fall asleep, overall amount of sleep at night) from tri-axial accelerometry and photoplethysmography. The Fitbit Charge HR© was attached to the child's non-dominant wrist on Friday (PM) by the trained research assistant. Parents and children were instructed to keep the device on the non-dominant wrist for 48 h, removing it only for water-based activities (eg, swimming and bathing).

The ActiGraph GT9X Link© (ActiGraph LLC., Pensacola, FL, USA) is a scientific-grade wrist-worn tri-axial accelerometer that is commonly-used in children's activity and sleep research [5]. The ActiGraph GT9X Link© was fastened to the child's non-dominant wrist on Friday (PM), directly above the Fitbit Charge HR©. Parents and children were instructed to keep the device on the non-dominant wrist for 48 h following the same protocols as the Fitbit Charge HR©.

Parents were given a sleep log to record their child's bed and wake times and any periods of non-wear across devices. Research assistants sent two daily text reminders (one AM, one PM) to the parent/guardian to complete the sleep log.

2.3. Statistical analysis

All devices were retrieved from the child/parent on Sunday (PM). The sleep characteristics of total sleep time (TST) and bed/wake times were chosen as other sleep characteristics (eg, sleep quality), were not available from all devices. These data were downloaded/extracted as follows: The Beddit 3 Sleep Monitor© via the Beddit 3 Sleep Monitor© and Apple Health© mobile applications, the Fitbit Charge HR© via a third-party research platform, Fitabase© (Small Steps Labs LLC, San Diego, CA, USA), and the ActiGraph GT9X Link© via ActiLife software (v6.13.3) using Sadeh sleep algorithms (1-minute epochs) for children [5]. Descriptive sleep data (ie, mean, SD, range) for TST (minutes/night), bed/wake times, and time in bed (elapsed time in minutes between bed and wake time) were estimated. Bland Altman plots and Pearson correlation coefficients assessed the level of agreement for TST and mean absolute differences for bed and wake times were calculated across sleep measures. All analyses were conducted using Stata, version 14.1 (Stata Corp LLC, College Station, TX, USA).

3. Results

Thirty children provided, on average, 52 observation nights (range 46–56 nights) from a possible 60 observation nights. Child observation nights with missing data were due to device malfunction or wear non-compliance ($n = 14$), child sleeping in another location/not directly on Beddit 3 Sleep Monitor© ($n = 14$)' or parents forgetting to complete the daily sleep log ($n = 4$). Table 1 presents descriptive sleep information. Across the four sleep measures, TST ranged from 458 min/night (ActiGraph GT9X Link©) to 613 min/night (Parent report), and time in bed ranged from 571 min/night (ActiGraph GT9X Link©) to 613 min/night (Parent report). Mean bed and wake times ranged from 8:46$_{PM}$ to 9:03$_{PM}$, and 6:52$_{AM}$ to 7:16$_{AM}$, respectively. Table 2 illustrates the mean absolute difference across the four sleep measures for bed and wake times. For bed times, the smallest absolute difference was between the ActiGraph GT9X Link© and the Beddit 3 Sleep Monitor© (±5.5, SD ± 8.0, range 0–36 min). For wake times, the smallest absolute difference was between the Fitbit Charge HR© and the ActiGraph GT9X Link© (±13.7, SD ± 20.8, 0–96 min). Pearson correlation coefficients were moderate between all four sleep measures (range $r = 0.30–0.71$, $p < 0.05$) (Fig. 1). Bland–Altman plots indicated the highest level of agreement for TST was between Beddit 3 Sleep Monitor© and Fitbit Charge HR© (mean difference −11.7, limits of agreement: 119.0, −142.4 min).

Table 1
Mean total sleep time and bed/wake time descriptive information.

Sleep Measure	Child Obsv.	Total Sleep Time (minutes)				Time in Bed[a] (minutes)				Bed Time (HH:MM)			Wake Time (HH:MM)		
		Mean	(±SD)	Range		Mean	(±SD)	Range		Mean	Range		Mean	Range	
Beddit 3 Sleep Monitor©	46	514	67	347	631	573	63	423	710	9:00 PM	6:34 PM	12:06 AM	7:04 AM	5:13 AM	9:31 AM
Fitbit Charge HR©	50	530	63	395	707	577	68	422	737	8:46 PM	6:14 PM	12:08 AM	6:52 AM	4:11 AM	8:38 AM
ActiGraph GT9X Link©	56	458	67	257	614	571	68	404	722	8:56 PM	6:17 PM	12:09 AM	6:53 AM	4:07 AM	9:47 AM
Parent Report	56	613	63	435	727	613	63	435	727	9:03 PM	6:15 PM	11:45 PM	7:16 AM	5:45 AM	9:37 AM

Obsv = Observation Nights, SD=Standard Deviation.
[a] Time in Bed calculated as duration between bed and wake time.

Table 2
Absolute differences (minutes) in bed and wake times by measurement.

Mean Absolute Difference in Minutes (±SD, Range)	Bed Time			
	Beddit 3 Sleep Monitor©	Fitbit Charge HR©	ActiGraph GT9X Link©	Parent Report
Wake Time				
Beddit 3 Sleep Monitor©	n/a	6.9 (±7.7, 0–34)	5.5 (±8.0, 0–36)	21.5 (±20.2, 0–89)
Fitbit Charge HR©	18.5 (±29.6, 0–148)	n/a	5.9 (±5.7, 1–29)	18.9 (±16.8, 1–68)
ActiGraph GT9X Link©	23.2 (±31.6, 0–152)	13.7 (±20.8, 0–96)	n/a	20.7 (±20.6, 0–90)
Parent Report	22.5 (±27.6, 0–116)	29 (±35.5, 1–171)	33.2 (±33.1, 0–143)	n/a

4. Discussion

This is among the first studies to compare common free-living sleep outcomes of elementary-school aged children across multiple measures. Overall, the results from the comparisons across different sleep measures show a moderate agreement in the estimation of TST and acceptable accuracy across sleep measures in determining bed and wake times.

Results from this study present similar patterns from studies comparing estimates of TST across different sleep measures. In this study wrist-worn monitors estimates of TST were 458 and 530 min/night (mean), which is similar to a recent meta-analysis of actigraphy-reported pediatric nighttime sleep in elementary school-aged children (440–510 min per night) [1]. In addition, parental report of children's sleep provided the highest estimates of TST which is similar to most pediatric sleep studies comparing parental report to objective measures of sleep [4]. This is not surprising given that parental reports of TST are susceptible to reporting biases and inaccuracies when compared to objective measures of TST [1]. Hence, researchers must interpret their findings with caution when using subjective proxy measures to quantify children's TST. Another pattern that emerged in this study is that Fitbit Charge HR© provided the highest TST estimates across the three objective measures. This finding is consistent with other studies using wrist-worn Fitbit© devices – albeit in different populations and settings – where studies comparing Fitbit© devices and research-grade accelerometers to PSG in either healthy adolescents or adults have found the wrist-worn methods overestimate sleep duration [10,11,14–17]. The Fitbit Charge HR© uses an unknown proprietary algorithm, and it remains unclear whether or not the algorithm combines movement and plethysmography data (ie, heart rate) to improve the accuracy of sleep/wake detection [9]. On the other hand, actigraphy devices solely use raw 'counts' and translate to sleep-wake scores based on computerized scoring algorithms [5].

This study was one of the first to report healthy children's free-living sleep estimates from a BCG-based commercial device in comparison to other sleep measures. Similar to the capabilities of the Fitbit Charge HR©, the Beddit 3 Sleep Monitor© captures physiological (BCG-based data) and movement properties (pressure applied to bed detection strip) and it is unclear if a combination of the two data-sources quantify sleep outcomes. Interestingly, results from the Bland–Altman plots showed the highest agreement between these two devices for TST, and some of the smallest absolute differences across bed and wake times. Chung and colleagues compared sleep outcomes of a BCG-based device versus PSG in 10 healthy adult subjects and reported moderate-to-strong agreement between the two devices (Cohen's κ 0.67) [18].

The variability and intricacies of proprietary sleep-algorithms, sensitivity settings, and statistical weightings across objective sleep devices [7] – and its subsequent impact on TST – is illustrated by examining the time elapsed by bed and wake times (referred herein as time in bed). Across the three objective sleep measures, the TST estimates (mean) varies from 458 to 530 min/night, compared to time in bed estimates (mean) which vary from 571 to 577 min/night. Put simply, the objective devices seem to 'agree' when children are falling asleep and waking, yet, their classification criteria of 'sleep' categorize sleep/wake periods differently while children are in bed. This leads to vastly different TST estimates. This underlines the importance for researchers, regardless of objective measure selected, to identify and stay consistent with sleep scoring protocols throughout the duration of their study or intervention to minimize misinterpreting measurement error as an effect.

Strengths of this study include the free-living setting to capture children's natural sleep, the comparison of multiple objective sleep measures, and the inclusion of a commercially-available BCG-based sleep tool (Beddit 3 Sleep Monitor©). However, this study was not without limitations. The study sample was predominately non-Hispanic white, the sleep devices herein do not represent the breadth of devices available to researchers and these data only represent weekend nights. In addition, this study did not include a gold-standard criterion for sleep (ie, PSG) to compare with any of the sleep estimates, although this was by design.

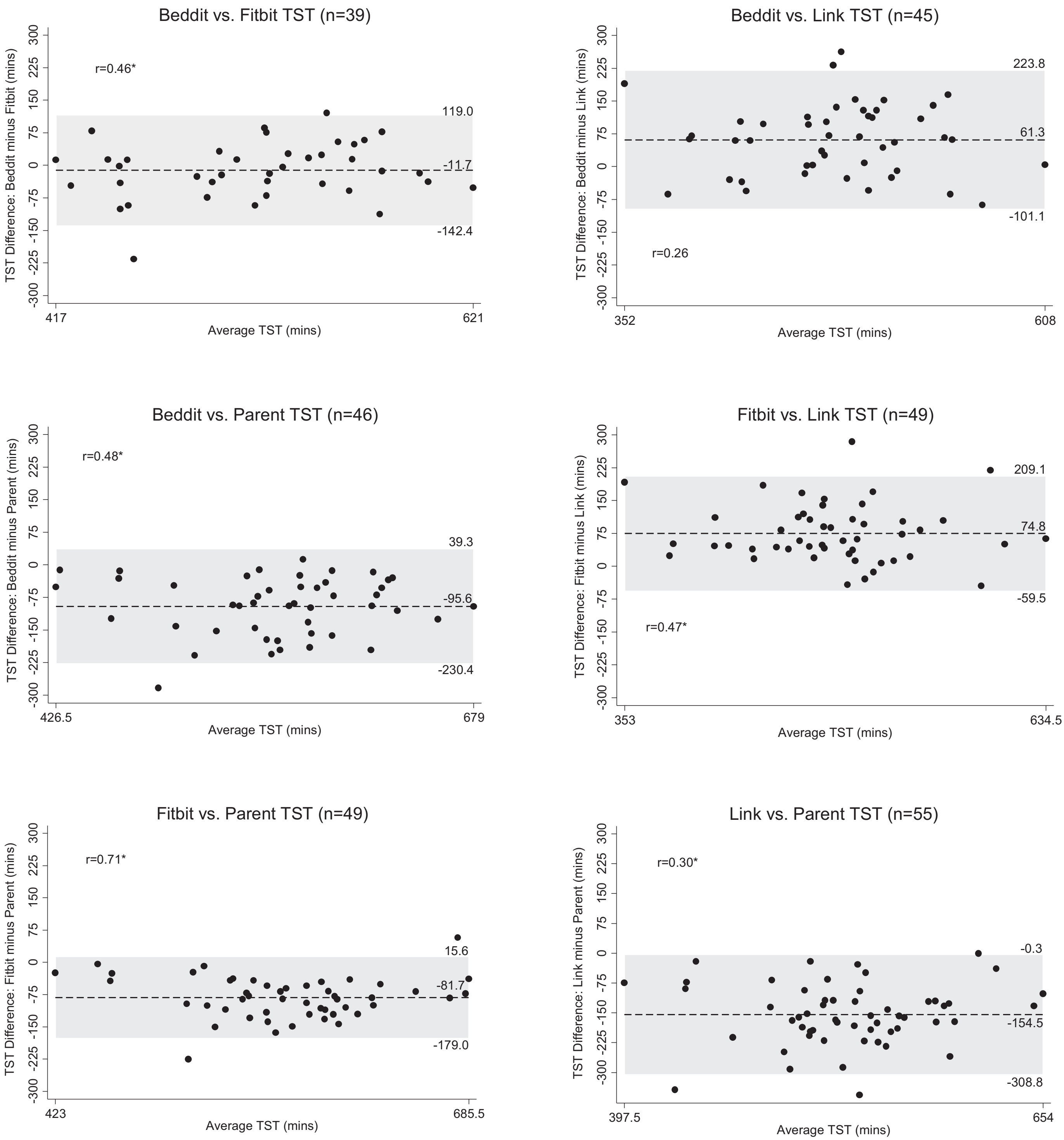

Fig. 1. Bland Altman plots illustrating agreement between Beddit 3 Sleep Monitor©, Fitbit Charge HR©, ActiGraph GT9X Link©, and Parent Report of children's total sleep time (TST). * Statistical significant correlation ($p < 0.05$).

5. Conclusion

In conclusion, the findings from this study show a high level of agreement of when a child goes to sleep and wakes up across a variety of sleep measures; however, more work is needed to classify TST once the sleep period has commenced. It is the authors recommendation that researchers accompany objective measures of sleep with subjective measures (eg, sleep log, daily sleep diary) to compare recognized sleep periods (ie, time in bed) across measures [19].

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Conflict of interest

The authors have no conflict of interest to report.

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