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Validation of sleep-wake estimation from thigh-worn accelerometers against polysomnography in adolescents with and without mental disorders

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Abstract

Background To validate the estimation of sleep-wake patterns using thigh-worn accelerometers against polysomnography —the gold standard for sleep assessment—in adolescents with and without mental disorders from the Danish High Risk and Resilience Study, addressing the feasibility of simpler methods in clinical populations.

Methods 146 adolescents (ages 15–17) underwent one night polysomnography and concurrent thigh-worn accelerometry. Sleep-wake parameters—total sleep time, sleep efficiency, sleep onset latency, wake after sleep onset (WASO), and number of awakenings —were compared using ActiPASS software. Reliability was evaluated in the full sample and in subgroups of participants fulfilling and not fulfilling criteria for an Axis I mental disorder. Sensitivity and specificity were estimated based on cut-off values.

Results ActiPASS underestimated total sleep time by 51.7 min, sleep efficiency by 1.4%, and number of awakenings by 13.7, and overestimated sleep onset latency by 23.7 min and WASO by 25.7 min compared to polysomnography. Intraclass correlation coefficients (ICCs) were high for total sleep time (0.88), moderate for sleep efficiency (0.55), sleep onset latency (0.69), and WASO (0.64), but low for number of awakenings (0.39). Group-level ICCs were marginally higher in the "No Mental Disorder" group. Sensitivity was perfect and specificity high for total sleep time < 360 min. Sensitivity was high and specificity moderate for WASO > 50 min and sleep onset latency > 30 min.

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Conclusions Thigh-worn accelerometers showed potential for monitoring of sleep-wake patterns and screening for sleep disturbances in adolescents with mental disorders, demonstrating moderate to high reliability for key sleep-wake metrics.

Keywords Validation study, Polysomnography, Accelerometry, Adolescents, Mental disorders

Background

Polysomnography (PSG) is the gold standard for sleep measurement, providing detailed insight into sleep stages, movement, and physiological parameters in healthy and diseased sleep. However, its complexity and intrusiveness limit its applicability for wider use and long-term monitoring of sleep-wake (SW) rhythmicity, particularly in vulnerable groups such as adolescent users of mental health services. The use of accelerometers, which infer SW patterns from movement, may offer a practical alternative for long-term monitoring, although at the cost of detail [1]. Wrist worn accelerometers are widely used because of their affordability, ease of use, and ability to track sleep over extended periods in naturalistic settings [2, 3]. However, accelerometers traditionally worn on the wrist, are prone to misidentifying wakeful states with minimal movement as sleep, or limb movements during sleep as wakefulness [4]. Additionally, the reliability of accelerometers decreases with increasing sleep fragmentation, as is typical of individuals with severe mental disorders and comorbid sleep disturbances [5]. In this regard, thigh-worn accelerometers, positioned closer to the body's center of mass, may provide a more stable and accurate measure of movement and posture [6, 7]. Thigh-worn accelerometers allow for extended tracking, which is essential for capturing day-to-day variability missed by single-night PSG recordings. Furthermore, thigh-worn devices, can differentiate between sitting and lying positions, potentially improving the accuracy of the assessment of circadian SW rhythmicity. However, validation studies of thigh-worn accelerometry against PSG in vulnerable adolescent populations are lacking.

Sleep disturbances are highly prevalent in adolescents with mental disorders and negatively impact disease progression and overall functioning [8, 9]. Attention deficit hyperactivity disorder (ADHD) is linked to daytime sleepiness and irregular sleep patterns [10]. Depression [11] and anxiety [12] are associated with insomnia and sleep problems. In children with autism spectrum disorder and comorbid anxiety, these conditions may predispose them to sleep disturbances [13]. The occurrence of sleep disturbances across neuropsychiatric disorders suggests a shared etiology, possibly involving desynchronization with the brain's master clock, the suprachiasmatic nucleus (SCN) [14]. Misalignment of peripheral clocks with the SCN has been associated with sleep and circadian rhythm disturbances in severe mental disorders such as schizophrenia, bipolar disorder, and depression [15, 16]. However, the role and onset of sleep and circadian rhythm disturbances in the development of mental disorders remain unclear [17, 18]. In adolescents at high-risk of clinical psychosis, circadian rhythm disruptions predict symptom severity at later stages of disease [19]. Similarly, insomnia symptoms significantly increase the risk of bipolar disorder later in life [20] and has been linked to increased suicidal risk in adolescents with depression [21] and first episode psychosis [22]. Therefore, early identification of SW disturbances may enable timely interventions that improve both sleep and mental health outcomes [23]. However, this requires feasible methods for both large-scale and long-term monitoring.

In this study we validated the reliability of thigh-worn accelerometry in estimating SW parameters compared with PSG. We further aimed to compare the reliability between groups of adolescents with and without Axis I mental disorders. Finally, we aimed to evaluate the clinical utility of SW estimation from thigh-worn accelerometry by estimating the sensitivity and specificity in identifying SW patterns using predefined cut-off values indicative of sleep disturbances.

Methods

Participants

We included a subsample of 170 out of 427 participants from the Danish High-Risk and Resilience Study – VIA 15 [24] (the VIA 15 Study), a longitudinal cohort study [25] that began in 2013 with the aim of early identification of both risk and protective factors for the development of severe mental illness. The original cohort consisted of 522 participants, identified from the Danish civil registration system [26], and the Danish Psychiatric Central Research Register [27] with at least one biological parent diagnosed with a schizophrenia spectrum disorder ($N = 202$), (ICD-10 codes: F20, F22, F25, or ICD-8 codes: 295, 297, 298.29, 298.39, 298.89, and 298.99), or bipolar disorder ($N = 120$), (ICD- 10 codes: F30, F31, or ICD-8 codes: 296.19, 269.39), and population-based controls ($N = 200$), where neither parent had any of these disorders. The participants in this substudy were recruited from June 2022 through May 2024 as part of the general information procedure of the VIA 15 Study [24]. The participants were invited to join the PSG-examination, following which arrangements were scheduled for a specific date by telephone call or by SMS. The participants received a gift certificate of 300 DKR (≈42 USD). Of the 170 PSG recordings with synchronous accelerometry data, five were excluded because PSG-equipment had failed to record and 19 were excluded because technical problems with the accelerometers resulted in partly missing or complete missing data. In total, 146 participants were included in the analyses.

Polysomnography

One night of PSG was conducted at the participants' homes, preferably on weekdays Monday through Thursday. Somnomedics Somno HD devices with the Somnomedics EEG + 32-channel headbox attached were used for all recordings. We used an extended montage of 20-channel electroencephalography (EEG), bilateral electrooculography (EOG) at the outer canthi, electrocardiography (ECG), and submental electromyography (EMG), all positioned according to the American Academy of Sleep Medicine (AASM) 10–20 system guidelines [28]. All PSGs were administered by the same two researchers (first and second authors). Sleep staging was based on derivations F4, C4, and O2 or, alternatively, F3, C3 and O1 according to the AASM guidelines [28]. All PSG recordings were conventionally scored by either one of two trained technicians at Zealand University Hospital, - the Department of Neurology or the Danish Center for Sleep Medicine. Participants registered times of lights off and lights on in a sleep diary which were used as temporal marks for analysis start and end in PSG reports.

Accelerometry

The participants wore accelerometers from SENS Innovation [29] concurrent with the PSG-recording. These wireless, thigh-worn devices are designed to collect accelerometric information on movement and physical activity. Each sensor is small (45 × 4.5 × 23 mm), lightweight (7 g), waterproof, and equipped with a triaxial accelerometer sampling at 12 Hz with a range of ± 4G. The sensor was embedded within a hypoallergenic band-aid and attached approximately 10 cm above the lateral epicondyle of either the left or right knee. Sensors were retrieved along with PSG equipment, and raw-data were transferred wirelessly via a smartphone or tablet application to the SENS innovation secure cloud upon return to our facilities.

Sleep estimation software

ActiPASS is an open-source tool designed to detect physical behaviors, including postures [30] and sleep [4] from raw accelerometer data collected via tri-axis accelerometers placed on the front of the thigh. In this study, the SENS accelerometers were positioned on the lateral part of the thigh, requiring adjustment of the accelerometer axes before processing the data. The raw accelerometer data were downloaded from the SENS Innovation secure cloud and processed locally with ActiPASS software (version 2024.05.4) [31]. The MATLAB code for the Skotte Sleep Algorithm that is currently used in ActiPASS is available at GitHUB [32].

ActiPASS includes a feature to automatically identify "time in bed" from multiple-day recordings. However, this function requires more than 48 h of continuous data. Therefore, the "lights off" and "lights on" times from the PSG recordings were manually typed into ActiPASS as the time in bed. The software then estimated the following sleep variables using its built-in algorithm [30]: total sleep time (TST) – the total time participants slept between lights off and lights on; sleep efficiency (SE) – the percentage of recorded time spent asleep until the final awakening; sleep latency (SL) – the time from lights off to the first instance of sleep; awakening index (AW) – the number of awakenings longer than 10 s per hour and; wake after sleep onset (WASO) – the total time awake after the first sleep onset until the last wake up.

Mental disorders

Information about lifetime and present axis I mental disorders was obtained with the Kiddie Schedule for Affective Disorders and Schizophrenia – Present and Lifetime Version - KSADS-PL [33], a semistructured interview conducted with both participants and caregivers, as part of the assessment in the VIA 15 Study. For this study we only used the present axis I diagnoses. The interviews were conducted by staff members with an educational background of nurse, medical doctor, or psychologist, and diagnoses were determined at regular consensus conferences attended by a specialist in child and adolescent psychiatry.

Medication use

The participants were asked about the use of prescription medication within the last 24 h on the day of PSG-recording. The prescription medication was categorized as either "ADHD central stimulant", "ADHD nonstimulants", "melatonin" or "other" on the basis of the active pharmaceutical ingredient of each product.

Statistical analysis

All the statistical analyses were conducted with IBM SPSS version 29 and RStudio 2024.04.2. *P*- values for Table 1 were calculated with independent samples t tests for continuous normally distributed variables (age), chi-square tests for categorical variables (sex, familial high-risk status, and medication), and Mann-Whitney U tests for continuous nonnormally distributed variables (BMI). PSG recordings of sleep parameters are considered the gold standard to which accelerometer data are compared to. Prior to analysis, the recording times of the accelerometers were synchronized with the "lights off" and "lights on" times of the PSG recordings on the

Table 1 Sample characteristics

	All (*N* = 146)	**"No Mental Disorder" Group (*N* = 97)**	**"Any Mental Disorder" Group (*N* = 49)**	***p*-value: "Any Mental Disorder" vs. "No Mental Disorder" group**
Age (SD)	16.33 (0.51)	16.34 (0.52)	16.33; (0.51)	0.90[a]
Sex, Male (%)	66 (45.2)	45 (47.9)	21 (42.0)	0.57[b]
BMI (kg/m^2)	22.18 (4.0)	21.93 (3.87)	22.63 (4.22)	0.44[c]
Familial high-risk status:				0.49[b]
- Schizophrenia	55	35	19	
- Bipolar Disorder	38	23	15	
- Control	53	38	15	
Any axis I diagnosis: N (%)	49 (33.6)	0 (0)	49 (100)	
> 1 axis I diagnosis	20 (13.7)		20(40.8)	
Medication: N (%)				0.07[b]
- ADHD (Stimulants)	3 (2.1)	0 (0)	3 (6,0)	
- ADHD (Non-stimulants)	1 (0.7)	0 (0)	1 (2,0)	
- Melatonin	2 (1.4)	0 (0)	2 (4,0)	
- Other (Non-stimulants)	29 (19.9)	17 (17.5)	12 (24.0)	

Dysthymia, Social Phobia, Specific Phobia, Generalized Anxiety Disorder, Adjustment Disorder with Anxiety, 766 Posttraumatic Stress Disorder, Unspecified Feeding or Eating Disorder, Oppositional Defiant Disorder, Other Specified 767 Feeding or Eating Disorder, and Alcohol Use Disorder. ADHD stimulants included brand names Medikinet, Gabapeltin and 768 Concerta. ADHD non stimulants included Intuniv. Other medication includes asthma inhalants, antidepressants, antiepileptics, 769 anti-acne agents, and contraceptives

Abbreviations: *BMI* body mass index, *ADHD* attention deficit hyperactivity disorder

basis of information from sleep diaries. The mean differences between PSG and accelerometry for the included SW parameters were calculated and compared with paired samples t tests. Bland-Altman plots were generated for visual inspection of the agreement between PSG and accelerometry. To assess the reliability between PSG and accelerometry, we calculated the intraclass correlation coefficient (ICC) for all sleep parameters from a two-way mixed effects model with consistency as definition (ICC(3,1)) [34]. ICCs were calculated for the full sample and for groups stratified into an "Any Mental Disorder" group with participants meeting the criteria for at least one Axis I diagnosis but allowing for multiple diagnoses, and a "No Mental Disorder" group comprising those not meeting the criteria for any Axis I diagnosis. This stratification aimed to assess the utility of thigh-worn accelerometry, specifically in adolescents with mental disorders, using the "No Mental Disorder" group as a nonclinical reference and the "Any Mental Disorder" group to model a clinical population of adolescents with mental disorders. Because this study is based on a selected high-risk population, we tested for the interaction effect of the familial high-risk (FHR)- group on the agreement between PSG and accelerometry measures. The difference in sleep measures was estimated using Method (Actigraphy or PSG), Group (FHR-schizophrenia, FHR-bipolar disorder or Control), and their interaction (Method × Group) as predictors. Finally, we generated receiver operating characteristic (ROC) curves with the PSG measurements as a reference to assess the sensitivity and specificity of accelerometry to identify cases on the basis of cut-off values at clinically relevant levels: TST < 360 min; WASO > 50 min; and SL > 30 min.

Results

The sample characteristics of the 146 ethnic Danish adolescents are summarized in Table 1. Significant between group differences were found in terms of medication use. Between-group differences in age, sex, BMI, and FHR-status were non-significant. The distributions of all the diagnoses were as follows: ADHD (314.00; *N* = 20), autism spectrum disorder (299.00; *N* = 14), specific phobia (300.29; *N* = 8), and social anxiety disorder (300.23; *N* = 6). Diagnoses present in fewer than five participants included generalized anxiety disorder (300.02), separation anxiety disorder (309.21), major depressive disorder—single episode, mild (296.21), single episode, moderate (296.22), and recurrent episode, moderate (296.32), persistent depressive disorder (dysthymia; 300.4), posttraumatic stress disorder (309.81), adjustment disorder, with depressed mood (309.0) and with anxiety (309.24), alcohol use disorder (303.90), unspecified feeding or eating disorder (307.50), other specified feeding or eating disorder (307.59), persistent motor or vocal tic disorder (307.22), provisional tic disorder (307,21), Tourette's disorder (307.23), and oppositional defiant disorder (239.81). Collectively, these diagnoses accounted for *N* = 28 in the sample.

The medications used were ADHD stimulants (*N* = 3), ADHD nonstimulants (*N* = 1), melatonin (*N* = 2), and "other" medications (*N* = 29) including asthma inhalants, antidepressants, antiepileptics, antiacne agents, and contraceptives.

Table 2 Sleep-wake parameters as measured by polysomnography and accelerometry

	PSG (reference) (*N* = 146)	**Difference (PSG – accelerometry)**	***p*-value**
Total sleep time: min (SD)	447.0 (77.3)	51.7 (55.8)	< 0.001
Sleep efficiency: % (SD)	90.8 (8.2)	1.4 (11.5)	0.134
Sleep latency: min (SD)	23.2 (30.5)	−23.7 (31.8)	< 0.001
Awakenings: number (SD)	18.0 (10.1)	13.7 (9.2)	< 0.001
Wake after sleep onset: min (SD)	22.9 (34.2)	−25.7 (48.6)	< 0.001

Averages of sleep parameters from PSG and mean differences of measures between PSG and accelerometry from a paired samples t-test. Positive values of differences indicate that accelerometry underestimated the parameter compared to PSG. Negative values indicate that accelerometry overestimated the parameter compared to PSG. Values denoted as mean (SD)

Abbreviations: *PSG* polysomnography, *min* minutes

Table 3 Intraclass correlation coefficients for sleep-wake parameters at sample level and group levels

	N	**PSG vs. accelerometry TST**	**PSG vs. accelerometry SE**	**PSG vs. accelerometry SL**	**PSG vs. accelerometry AW**	**PSG vs. accelerometry WASO**
All	146	0.88 (0.83–0.91); *p* <.001	0.55 (0.37–0.67); *p* <.001	0.69 (0.57–0.77); *p* <.001	0.39 (0.16–0.56); *p* <.001	0.64 (0.49–0.74); *p* <.001
No mental disorder group	96	0.88 (0.82–0.92); *p* <.001	0.62 (0.43–0.74); *p* <.001	0.69 (0.53–0.79); *p* <.001	0.44 (0.16–0.63); *p* =.003	0.66 (0.48–0.77); *p* <.001
Mental disorder group	49	0.87 (0.77–0.93); *p* <.001	0.45 (0.03–0.69); *p* =.02	0.69 (0.45–0.82); *p* <.001	0.32 (−0.20–0.61); *p* =.09	0.61 (0.31–0.78); *p* <.001

ICCs (95% CI) from a two-way mixed effects model using consistency as definition. The "No mental disorder group" includes all participants without axis 1 diagnoses. The "Mental disorder group" includes participants with any present axis 1 diagnosis

Abbreviations: *ICC* intraclass correlations coefficient, *PSG* polysomnography, *TST* total sleep time, *SE* sleep efficiency, *SL* sleep latency, *AW* number of awakenings, *WASO* wake after sleep onset, *CI* confidence interval

The mean differences and standard deviations of the SW parameters from the PSG and accelerometry recordings are presented in Table 2. On average, accelerometry underestimated TST by 51.7 min, SE by 1.4%, and AW by 13, and overestimated SL by 23.7 min and WASO by 25.7 min.

The ICCs between the SW parameters measured with PSG and those measured with accelerometry are presented in Table 3. In the full sample, ICCs were moderate or good for TST, SE, SL, and WASO and poor or moderate for AW. Compared with those of the full sample, ICCs were higher in the "No Mental Disorder" group for SE, AW, and WASO and similar for TST and SL. In contrast, the ICCs in the "Any Mental Disorder" group were lower than those in the "No Mental Disorder" group for TST, SE, AW, and WASO but equal for SL. No significant interaction effect of FHR- group on agreement between measures was found for TST (p =.680), SE (p =.147), SL (p =.885), AW (p =.315) or WASO (p =.353).

Figures 1, 2, 3, 4 and 5 show Bland-Altman plots of the mean differences in TST, SE, SL, AW, and WASO between PSG and accelerometry. The wide confidence intervals indicate substantial variability in absolute differences across all parameters. A visual inspection of the plots suggests that the discrepancies between the methods increase as TST and SE decrease and as SL and WASO increase. The plot for AW generally shows poor agreement, with large discrepancies even at low values.

Figures 6, 7 and 8 show receiver operating characteristic (ROC) curves illustrating the ability of accelerometry to identify SW patterns at cut-off threshold levels. Accelerometry demonstrated perfect sensitivity and high specificity for detecting TST < 360 min, with strong discriminative ability across all thresholds. For WASO > 50 min, accelerometry showed high sensitivity and moderate specificity, with good overall discriminative ability. For SL > 30 min, the sensitivity was high, but the specificity was near chance, and the discriminative ability was moderate.

Discussion

This study aimed to validate the reliability of thigh-worn accelerometry for estimating SW patterns in adolescents by comparing it to the gold- standard of PSG. While differences in absolute values were observed, thigh-worn accelerometry demonstrated moderate to good reliability for all sleep parameters except AW. Stratification on the basis of diagnosis/no diagnosis did impact reliability. For three out of five parameters, performance was better in adolescents without mental disorders. However, group differences were small, and reliability in both groups was within the boundaries of same the categories of good and moderate. Additionally, no significant interaction effect was found between FHR group and agreement of measures on any included SW parameter, making thigh worn accelerometers equally reliable in FHR populations.

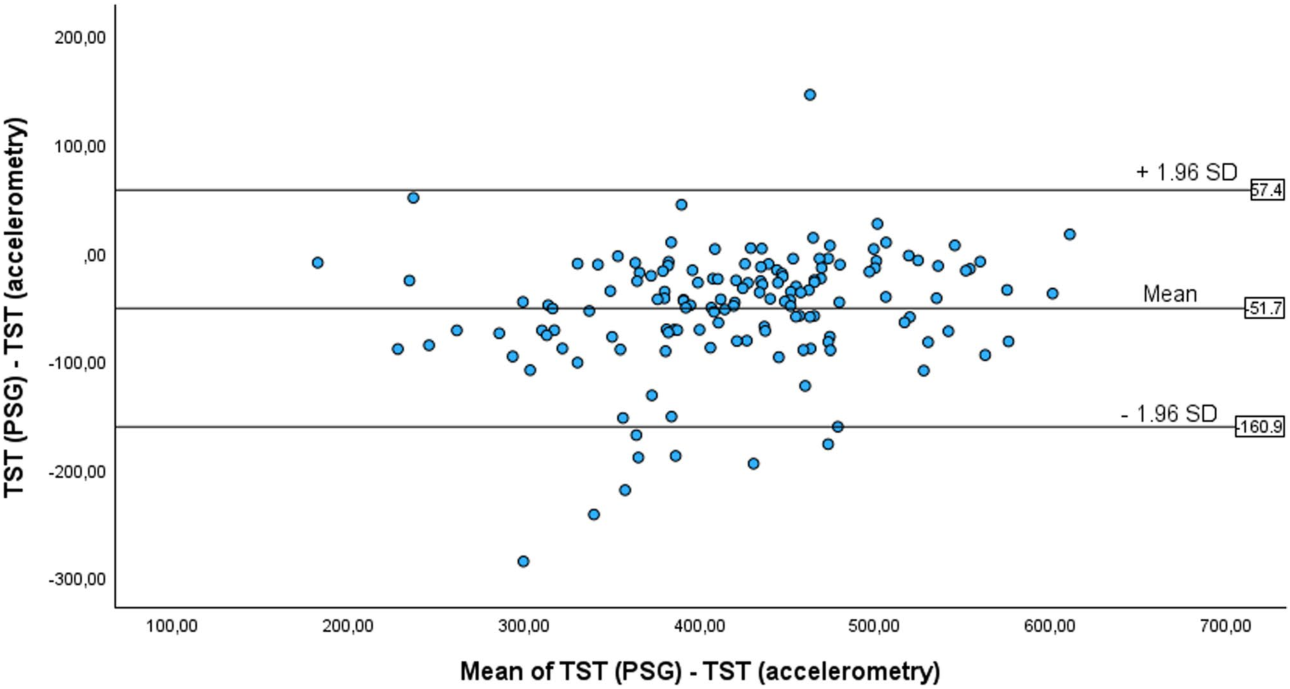

Fig. 1 Bland-Altman plot of differences between measures of total sleep time. Abbreviations: TST, total sleep time; PSG, polysomnography; SD, standard deviation

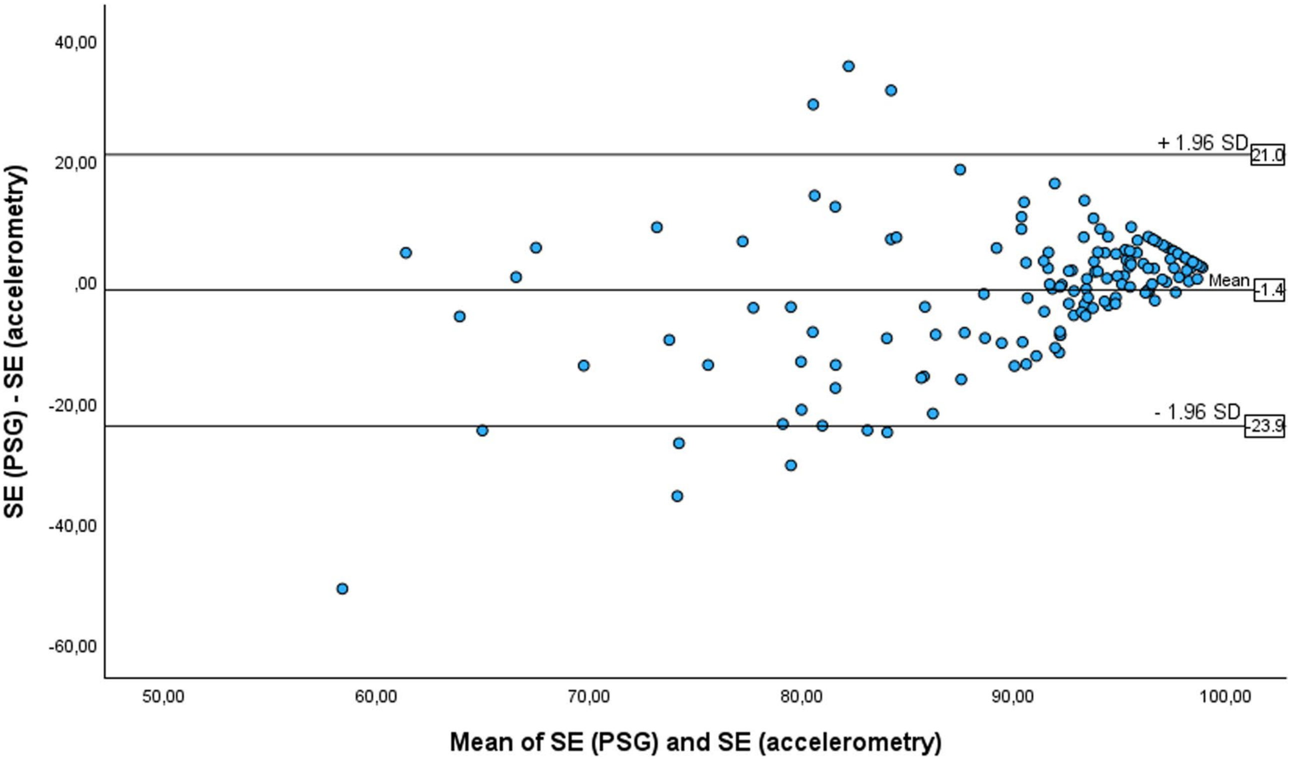

Fig. 2 Bland-Altman plot of differences between measures of sleep efficiency. Abbreviations: SE, sleep efficiency; PSG, polysomnography; SD, standard deviation

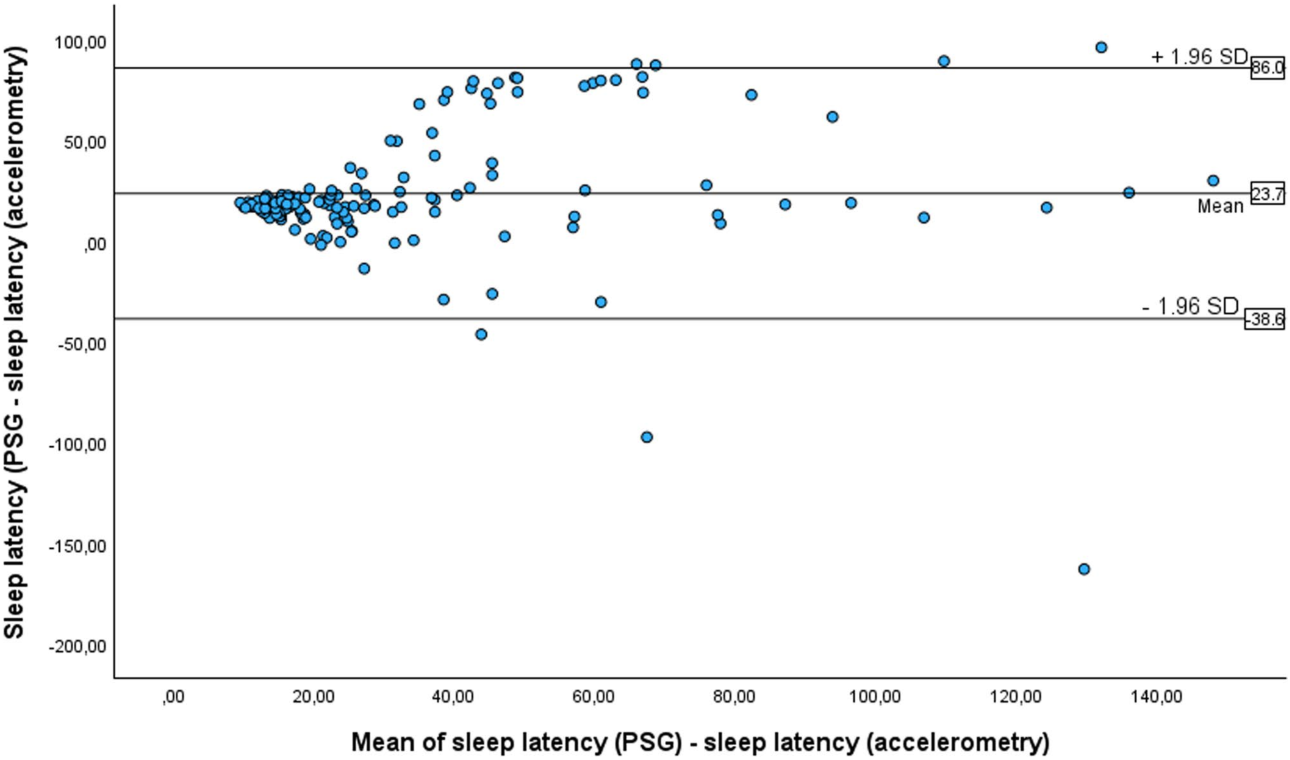

Fig. 3 Bland-Altman plot of differences between measures of sleep latency. Abbreviations: SL, sleep latency; PSG, polysomnography; SD, standard deviation

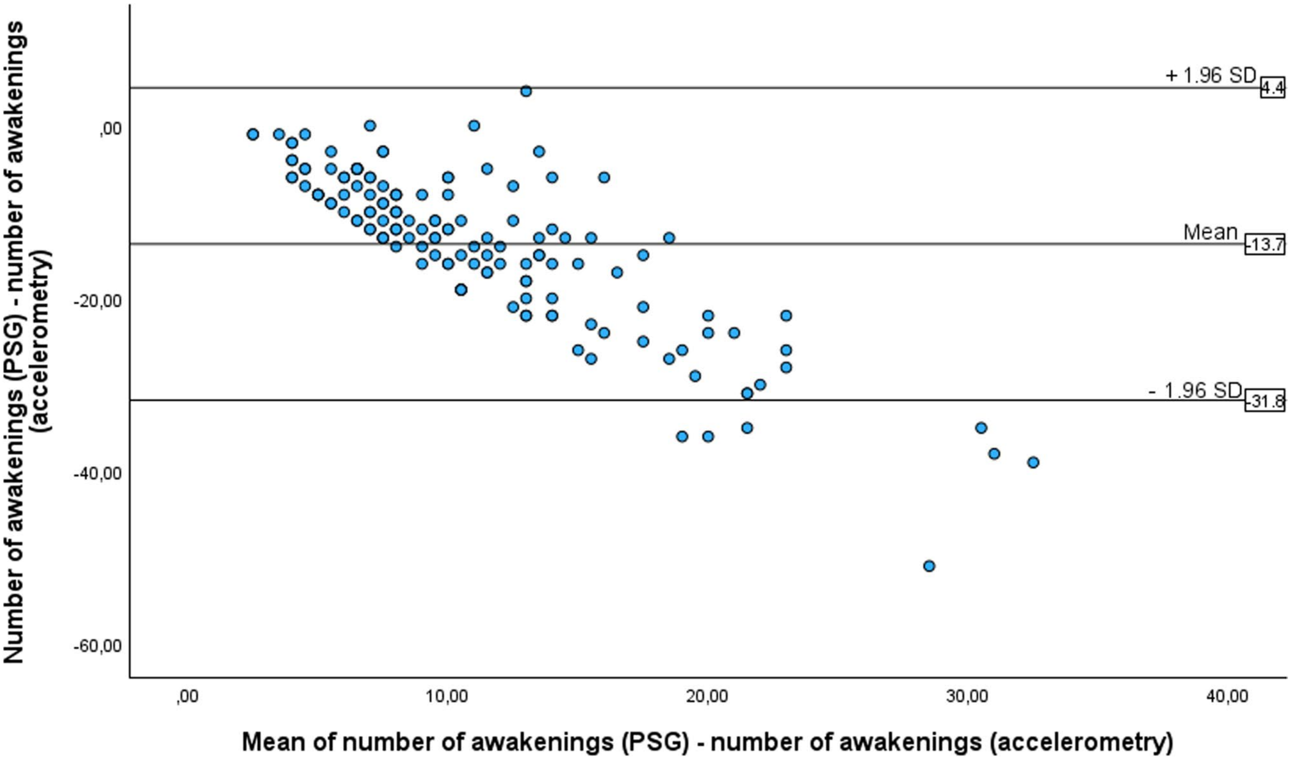

Fig. 4 Bland-Altman plot of differences between measures of number of awakenings. Abbreviations: AW, number of awakenings; PSG, polysomnography; SD, standard deviation

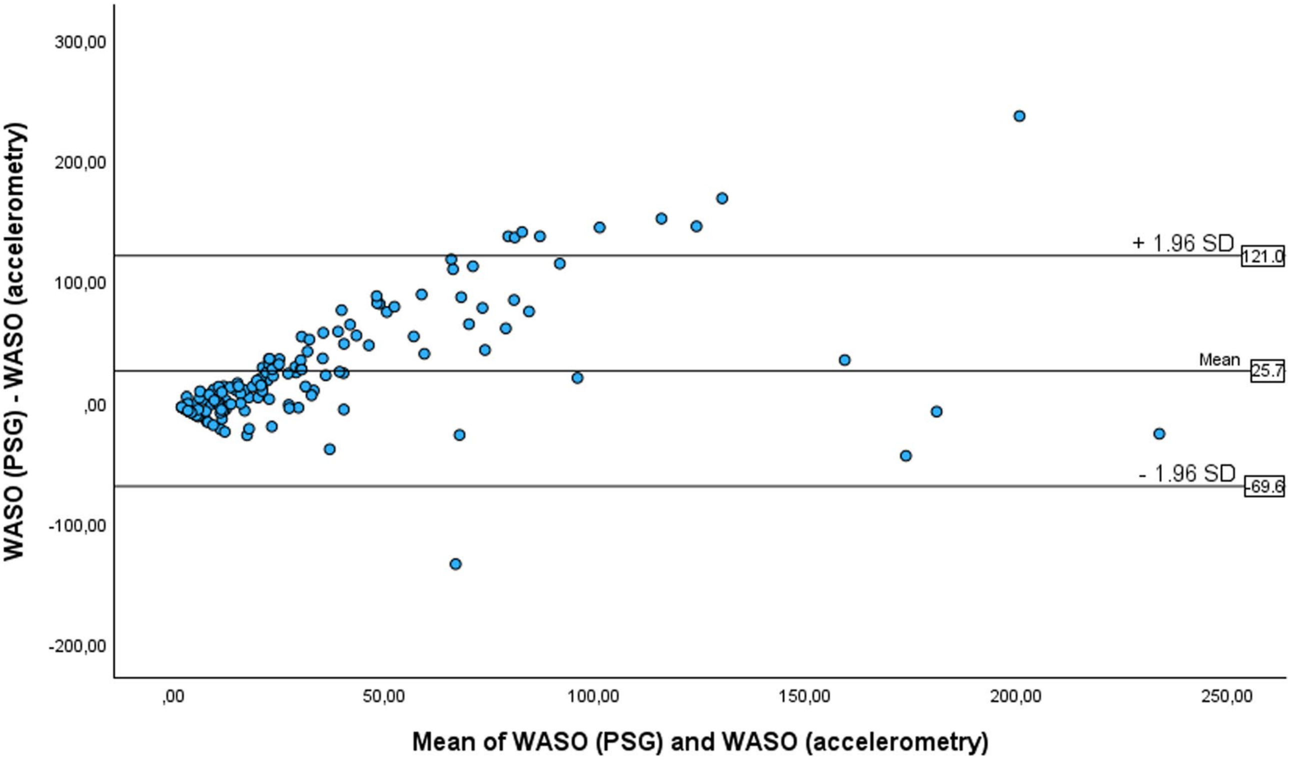

Fig. 5 Bland-Altman plot of differences between measures of wake after sleep onset. Abbreviations: WASO, wake time after sleep onset; PSG, polysomnography; SD, standard deviation

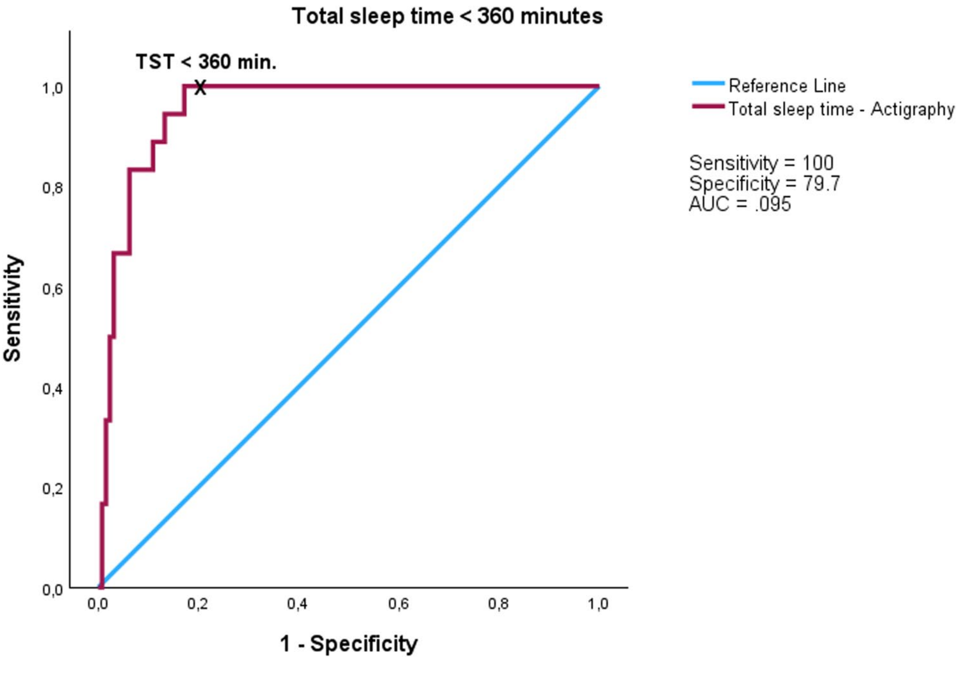

Fig. 6 ROC-curve displaying sensitivity, specificity, and AUC for cases with TST < 360 minutes. Notes: True TST values were defined by PSG. Sensitivity and specificity are shown for cut-off value TST < 360 min. AUC value reflects performance across all measured threshold values. Abbreviations: ROC-curve, receiver operating characteristic curve; TST, Total Sleep Time; AUC, Area Under the Curve

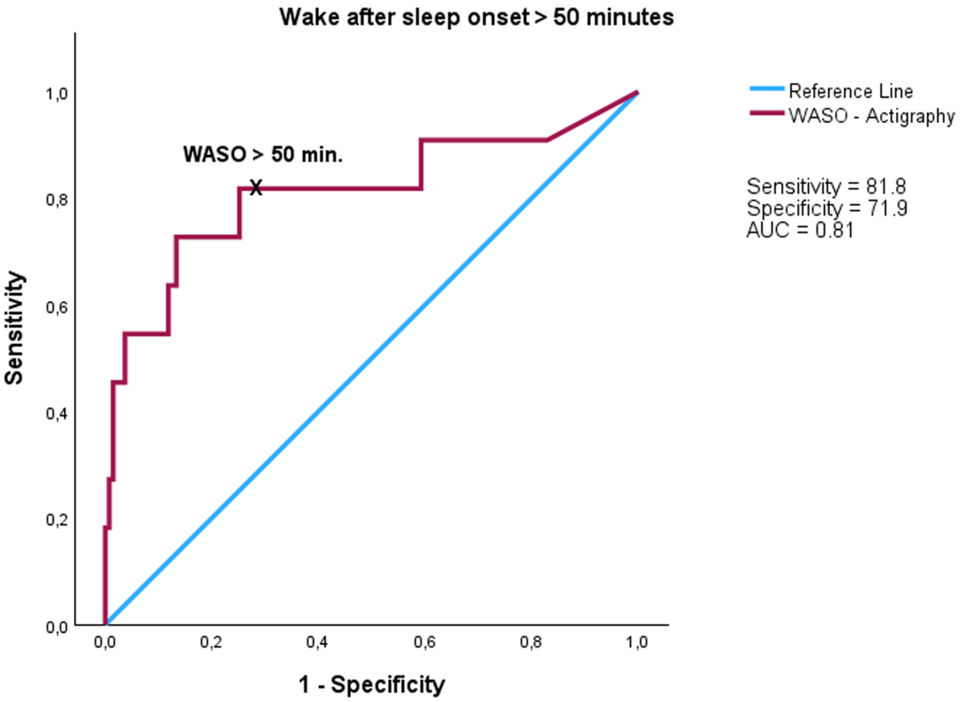

Fig. 7 ROC-curve displaying sensitivity, specificity, and AUC for cases with WASO > 50 minutes. Notes: True WASO values were defined by PSG. Sensitivity and specificity are shown for cut-off value WASO >50 min. AUC value reflects performance across all measured threshold values. Abbreviations: ROC-curve, receiver operating characteristic curve; AUC, Area Under the Curve

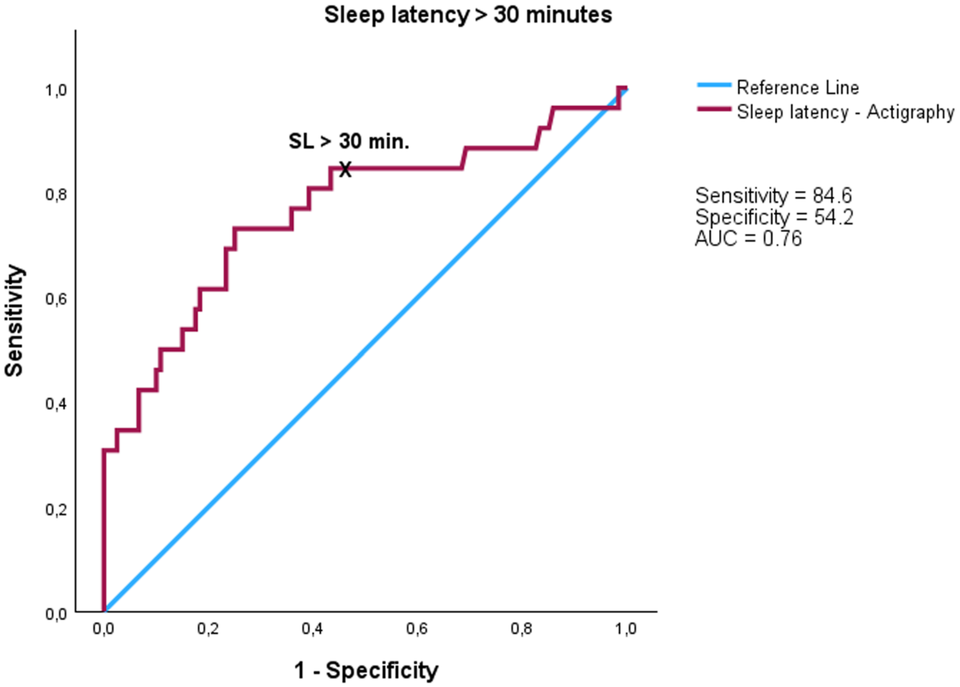

Fig. 8 ROC-curve displaying sensitivity, specificity, and AUC for cases with SL > 30 minutes. Notes: True values of SL were defined by PSG. Sensitivity and specificity are shown for cut-off value SL >30 min. AUC value reflects performance across all measured threshold values. Abbreviations: ROC-curve, receiver operating characteristic curve; AUC, Area Under the Curve

This suggests that thigh-worn accelerometers may offer a practical approach for assessing sleep across diverse populations, despite known limitations.

The observed tendency of accelerometers to underestimate total sleep time and overestimate wakefulness after sleep onset al.igns with prior findings in adolescent populations [35]. These biases likely stem from the method relying on movement to classify wakefulness, which can result in the misclassification of restless nonawake states as wakefulness [36, 37]. This may be relevant in individuals with fragmented or disrupted sleep, such as adolescents with mental disorders. In our sample, visual inspection of the hypnograms indicated that fragmented sleep often corresponded to an overestimated wake time and an underestimated sleep duration in the actograms, likely reflecting the limitations of the gradient-based approach of the ActiPass algorithm in detecting SW transitions [4]. While this limitation may be inherent to accelerometry, others have shown that accuracy can be increased by combining accelerometry with self-reported information from sleep diaries or questionnaires [38]. While accelerometry is never as precise as PSG is, it has advantages over PSG depending on the purpose of use.

A major strength of accelerometry is the capacity for extended monitoring periods, which allows it to capture a more representative picture of individual SW patterns and circadian rhythmicity over longer periods. This is particularly valuable in the context of circadian rhythm assessment and SW variability, where a single night of measurement may not adequately reflect habitual patterns. In populations with mental health conditions, where sleep disturbances are closely tied to symptom severity and treatment outcomes, the ability to monitor longitudinally is especially important [39]. In this context accelerometry offers a low-burden, cost-effective method that can be easily scaled for use in larger cohorts in naturalistic home settings, as we have shown in a previous study [40].

This study further supports the utility of thigh-worn accelerometry in detecting SW patterns associated with sleep disturbances, such as reduced TST and excessive WASO. In clinical practice, such information may aid in the diagnosis and management of sleep-related problems. For instance, identifying persistent sleep disturbances in adolescents with mental disorders could serve as an early warning sign of symptom deterioration [9]. While the sensitivity of accelerometers in detecting sleep latency (SL) above clinical thresholds was high, specificity was close to chance level. This suggests that relying solely on accelerometer-derived estimates in clinical settings could lead to false positives for prolonged SL. Given the known tendency of accelerometers to overestimate SL, a practical solution would be to adjust clinical cut-off values to account for this methodological bias. However, it remains critical to interpret accelerometry-derived data with an awareness of its inherent limitations. While it excels in providing a broad overview of sleep patterns, it lacks the precision of PSG for detailed analysis of specific sleep stages or physiological phenomena. Accelerometry is particularly suited to scenarios where the emphasis is on long-term trends or variability rather than moment-to-moment accuracy [41].

Future work might explore whether refining algorithms, to better account for sleep fragmentation, could further increase the accuracy of thigh-worn accelerometry. It may also explore how accelerometry might be integrated into interventions aimed at improving sleep health. For example, by tracking sleep patterns over time, accelerometry could help assess the effectiveness of behavioral or pharmacological treatments. Finally, studies could investigate how specific algorithms might be adapted for subgroups with unique sleep challenges, such as those with neurodevelopmental conditions or severe psychiatric disorders.

Some limitations to this study are the group size disparity between the “Any Mental Disorder” and “No Mental Disorder” groups which may affect the variance and impact ICCs. Additionally, although we did not identify any significant interaction effect from FHR group on reliability measures, both schizophrenia and bipolar disorder have hereditary components that predispose adolescents at familial risk to mental illness. While genetic influences on SW patterns in high-risk individuals are unclear, recent reviews suggest that the effects on sleep architecture are limited in those at risk for psychosis [42] or bipolar disorder [43]. Additionally, using the ActiPASS algorithm for SW estimation poses challenges, as it requires knowledge of thigh placement (not recorded by SENS accelerometers) and a 48-hour wear time, which participants did not meet. Sleep diaries were used for synchronization, but in 14 cases, actogram-hypnogram discrepancies indicated orientation issues, potentially affecting SW parameter estimates. Finally, some general problems with wrist-worn accelerometers are that they tend to mistakenly classify periods of low activity during the daytime as sleep and that they are much more accurate in detecting sleep than wakefulness [44]. Therefore, the reliability of sleep estimation may be greater in study designs where monitoring is restricted to periods where sleep is the predominant activity, than when monitoring over the full 24-hour cycle. However, due to the lack of validation studies, the extent to which thigh-worn accelerometers are vulnerable to this type of error is unknown.

Conclusions

In conclusion, thigh-worn accelerometry appears to be a reliable and practical method for estimating SW patterns and circadian rhythms in adolescents with and without mental disorders. While accelerometers have certain limitations, the ability to monitor multiple nights of sleep in a naturalistic setting offers distinct advantages. For both research and clinical practice, the integration of accelerometry into broader sleep health strategies has the potential to improve our understanding of sleep and its role in mental health and well-being. While polysomnography remains the gold standard, thigh-worn accelerometry is a practical and reliable alternative when PSG assessment is not feasible.

Abbreviations

ADHD	Attention deficit hyperactivity disorder
AUC	Area under the curve
AW	Number of awakenings
BMI	Body mass index
ECG	Electrocardiography
EEG	Electroencephalography
EMG	Electromyography
EOG	Electrooculography
FHR	Familial high-risk
ICC	Intraclass correlation coefficient
ICD	International Classification of Diseases
PSG	Polysomnography
ROC	Receiver operating characteristic
SE	Sleep efficiency
SL	Sleep latency
SW	Sleep-Wake
The VIA 15 Study	The Danish High Risk and Resilience Study
TST	Total sleep time
WASO	Wake after sleep onset

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Authors' contributions
MW, MN and LB conceived and designed the study. PJen supervised the writing process and made substantial contributions to the manuscript's content. PJoh and PH provided technical support for the ActiPass analyses and helped draft the Methods section. AS, SBR, AFB, AFL, MS and DHBS contributed to data collection and revised the text. MG, LV and MFK critically reviewed and contributed to the manuscript. ANG, NH, OM and AAET, oversaw overall project management and reviewed the manuscript. All authors read and approved the final manuscript.

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Data availability
Data available on reasonable request.

Declarations

Ethics approval and consent to participate
The study was approved by the National Science Ethics Committee (H-20067908) and the Danish Data Protection Authority (P-2019-273). Prior to assessment custody holders of all participants provided written informed consent, and participants gave assent upon oral and written information about the study.

Consent for publication
Not applicable.

Competing interests
The authors declare no competing interests.

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