Measuring High-Resolution Sleep Position in Adolescents over 4 Nights with Smartphone Accelerometers

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***Abstract*— Sleep position affects sleep quality and the severity of different diseases. Classical methods to measure sleep position are complex, expensive, and difficult to use outside the laboratory. Wearables and smartphones can help to address these issues to track sleep position at home over several nights. In this study, we monitor high-resolution sleep position in 13 adolescents over 4 nights using smartphone accelerometer data. We aim to investigate the distribution of sleep positions and position changes in adolescents, study their variability across nights, and propose new measures related to nocturnal body movements. We developed a new index, the mean sleep angle change per hour, and calculated three other measures: position shifts per hour, mean time at each position, and periods of immobility. Our results indicate that participants spent 56% of the time on the side (32% right and 24% left), 32% in supine, and 12% in prone position, similar to what happens in adults. However, adolescents moved more than adults during sleep according to all measures. There was some variability between nights, but lower than the inter-subject variability. In conclusion, this work systematically analyzes sleep position over several nights in adolescents, a largely unstudied population, and offers innovative solutions and measures for high-resolution sleep position monitoring in a simple and cost-effective way.**

***Clinical Relevance*— Our study characterizes sleep position in adolescents and provides novel unobtrusive methods and quantitative indices to monitor high-resolution sleep position at home during multiple nights.**

I. Introduction

Sleep position and nocturnal body movements are known to have an impact on sleep quality and the risk and severity of several diseases. For example, poor sleepers tend to spend more time on their backs than good sleepers [1], certain lateral and prone sleep positions are related to ocular hypertension, dry eye disease, and glaucoma [2, 3], and supine sleep position is associated with an increased occurrence of snoring and sleep apnea [4]. All these facts support that sleep position is a relevant variable when investigating sleep dynamics.

Most of the previous studies on sleep position have been conducted in adults, in a laboratory setting, for only one night. Currently, the gold-standard for sleep evaluation is polysomnography (PSG), which usually includes inertial sensors and cameras for measuring sleep position. However, PSG is an expensive, complex, and cumbersome test, as the patient has to spend an entire night in the hospital, attached to many wires and sensors, under the supervision of qualified healthcare professionals. For these reasons, PSG is performed in a single night, without considering the possible variability between nights. Another important limitation is that wearing PSG apparatus promotes supine sleep position [5], altering the normal sleep patterns. Besides, sleep position is classified into only four discrete values: supine, prone, right, and left. Recent studies have demonstrated that this broad categorization can be insufficient, and a higher resolution sleep position is required to better diagnose postural-dependent disorders such as positional sleep apnea [6,7].

The development of new wearable devices opens the possibility of investigating sleep position outside the laboratory in an unobtrusive, inexpensive, and simple way, thus facilitating studies on larger samples and a multi-night basis. Surprisingly, there are still very few studies taking advantage of these technologies for measuring sleep position over several days [8]. In 2021, our group presented a technique, based on smartphone accelerometer data, to obtain a high-resolution sleep position by monitoring the sleep angle [7] and developed the 'SleepPos' app, a smartphone application for high-resolution sleep position monitoring [9]. This approach, which takes advantage of the widespread use and powerful built-in sensors of smartphones, enables the measurement of sleep position at home over multiple nights.

At present, there are very few studies on the distribution of sleep positions and nocturnal body movements during free-living conditions, and even fewer on their variability across different nights. In addition, most of them focus on the adult population (18-65 years old), while there is little research on other age groups. Although it depends on the individual, it has been described that the preferred sleep position in adults is on the side, while the less frequent position is prone [8,10]. Nonetheless, this is strongly correlated with age. For instance, a PSG study with 50 subjects divided in 5 age groups found that all sleep positions occupied a similar proportion of sleep time in children, while the trend when approaching adulthood is a progressive preference for lateral positions and a reduction of prone positions, very marked in the elderly [11]. The number of movements and positional shifts during the night also tend to decrease with age [11]. These results agree with a cross-sectional study on sleep positions and body movements based on accelerometer recordings from more than 600 people [8], albeit it did not include subjects <20 or >65 years old.

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We considered interesting to measure sleep position in the adolescence, since it is a transition period from childhood to adulthood in which both brain and body undergo significant changes and sleep is essential to maintain physical and emotional health. It remains unclear whether the distribution of sleep positions and nocturnal body movements of teenagers will be closer to those of adults or younger children, and whether a similar pattern of sleep positions will be maintained during several nights in these subjects.

For all the above reasons, this study focuses on monitoring sleep position at home in adolescents over several nights. To do that, we propose to record and analyze triaxial accelerometer data by means of the 'SleepPos' smartphone application [9]. Our objectives are: 1) to investigate sleep position and position shifts in a sample of high-school students, 2) to investigate their variability over 4 nights, and 3) to propose new indices based on high-resolution sleep position and compare them with classical measures.

II. Materials and Methods

A. Study Population

Data were collected from October 2021 to December 2022, as part of a Research, Creation, and Service program from the Institute for Bioengineering of Catalonia (IBEC) and the Education Department of the Government of Catalonia, which is still ongoing. More than 250 students from 12 different public high schools in Catalonia participated in the project. All the procedures were approved by the Ethical Committee of Hospital Clínic de Barcelona, and written informed consent was given by the parents or legal guardians of all the students participating in the research.

Participants were able to measure their own sleep position during one or several nights with the 'SleepPos' app [9], developed by our research group. For the present study, to get a good compromise between sample size and the number of nights, we selected data from students who had recorded their sleep position during at least 4 nights. In case there were more nights, the first 4 nights were selected. The final dataset consisted of accelerometer recordings from 13 students: 9 men and 4 women, aged 14 to 16 years old, with a mean±std body mass index of 21.6±4.2 kg/m^2. Except for one subject (S06), the 4 nights were consecutive or belonging to the same week.

B. Procedure and Data Acquisition

Students and teachers had been trained in advance on how to install and use the 'SleepPos' app and how to wear the smartphone for the acquisitions at home. A fixation system comprising an elastic band was given to the participants, which was used to place the smartphone over the sternum, in the position suggested and tested in previous studies [7,9] (Fig. 1).

Triaxial acceleration data were recorded through the 'SleepPos' app, using the embedded accelerometers of the students' Android phones. Detailed information on the app and the procedures can be found in [9]. The sampling frequency depended on the smartphone model and ranged from 10 to 62 Hz. Once the acquisition was stopped by the user, raw data and processed data (described in the next section) were automatically saved in the phone's internal memory. Participants shared these data with the researchers involved in the study, by uploading them in secure online shared folders.

Figure 1. The smartphone is placed on the sternum with an elastic band and the 'SleepPos' app acquires accelerometer data to calculate the sleep angle and the amount of time at each position.

C. Signal Processing and Analysis

Accelerometer data were automatically processed and analyzed by the 'SleepPos' app but also exported to a computer for further analysis offline with Matlab custom-made scripts. For that purpose, all signals were resampled to 16 Hz to have the same sampling frequency, applying an anti-aliasing low-pass filter when necessary.

In the 'SleepPos' app, the raw accelerometry data are resampled to a uniform sampling rate of 10 Hz and then median filtered with a window of 60 s around each sample to remove high-frequency noise. After that, the sleep angle and stand angle at each time point are calculated, by identifying the orientation of the device relative to the gravity vector [7,9]. The sleep angle reflects the lateral rotation during sleep and thus the sleep position; while the stand angle indicates if the subject is lying in bed or sitting/standing. The sleep angle is also discretized into the 4 classic sleep positions, based on the thresholds of Fig. 1 and Fig. 2, which showed the best agreement with video-validated PSG in previous studies [7].

As a result of the analysis, the 'SleepPos' app displays, for each recording, a polar plot of the sleep angle as a function of time and a summary table with the minutes and percentage of time at each of the 4 classic sleep positions (Fig. 1). These were used to compute the total lying time, time out of bed, and distribution of sleep positions for each subject and night.

D. Indices of Sleep Position Shifts

Besides the measures computed by the 'SleepPos' app, accelerometer data were analyzed offline to extract indices related to nocturnal body movements and sleep position shifts. We calculated classical measures based on the 4 discretized positions, and a new index derived from the sleep angle to have a higher resolution. The classical indices were:

- The total number of position shifts and position shifts per hour. A 'position shift' was defined as a change from one classic sleep position to another (e.g., from supine to right). Only those sleep positions maintained for at least 1 minute were scored [1,8,11].
- The mean time maintaining the same sleep position [1]
- The number and percentage of periods of immobility, defined as those lasting 30 min or more in the same sleep position [1,11]

The proposed new index is the mean sleep angle change per hour. It can be calculated as the mean absolute value of the first derivative of the sleep angle, i.e.:

$$\frac{1}{T_{tot}}\sum_{i=1}^{N-1}|x[i+1]-x[i]| \quad (1)$$

where $x[i]$ is the sleep angle signal, T_{tot} the total time (in hours), and N the number of samples. The discontinuities when $x[i]$ gets close to 180 or -180° are corrected to avoid inaccuracies. Only the time lying in bed is considered.

Unlike the classical indices based on the broad categorization of sleep position into 4 discrete values, this index benefits from the higher resolution of the sleep angle and can detect small position shifts even if they occur in the same position, as illustrated in Fig. 2.

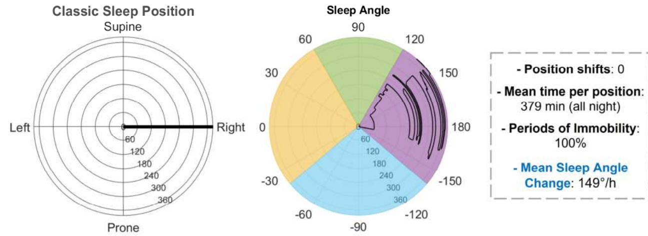

Figure 2. An example case where the subject sleeps on the right side all night, moving a lot (149°/h) but without position shifts in the classical four discrete values.

III. Results and Discussion

The mean and standard deviation of the total lying time were 7.3±0.9 hours, ranging from 4.4 to 9 h. The time out of bed was less than 3 minutes for all the subjects, representing only a 0.03% of the total duration of the recordings and being strictly 0 in 73% of the cases.

The distribution of classic sleep positions for all subjects and nights can be seen in Fig. 3. Each subject prefers certain sleep positions, even if there is some variability between nights. Overall, participants spent 32% of the lying time on the right side, 24% on the left side, 32% in supine, and 12% in prone position. Thus, the most common sleep position in these adolescents was on the side, while the less common was prone. Our findings are in line with the literature [1,8,10,11], which states that the distribution of sleep positions is influenced by age. Adults (20-80 years) have been reported to spend 50-70% of their sleep time on the side, 26-41% in supine and 1-9% in prone position [8,10,11]; while in children (3-12 years) all the positions occupy a more similar proportion of time: 53% on the side, 27% supine position, and 20% prone position [11].

The parameters related to body movements and sleep position changes are presented in Table I, showing the median, minimum, and maximum value for each participant. The mean sleep angle change per hour and the number of position shifts per hour for all subjects and nights are shown in Fig. 4.

On average, there were 16 positions shifts per night (2.15 per hour). Each position was maintained for an average of 29 min and there were 5 periods of immobility per night, representing a 35% of the positions adopted. Overall, the mean sleep angle change was 274°/h. All the parameters indicate that the adolescents moved a lot during the night. For example, in a study with a large sample of adults (20-65 years) the average number of shifts in sleep position per hour was 1.6 [8]. This agrees with previous studies, which observed a reduction in the number of posture changes progressively from childhood through adolescence to adulthood and elderly age [8,11,12].

Although there was some variability between nights, the intra-subject variability was much lower than the inter-subject variability. For example, both the mean sleep angle change and the number of position shifts indicate that S04 and S05 were the subjects who experienced more nocturnal movements, while S03 remained much quieter (Fig. 4, Table I).

TABLE I. Parameters related to sleep position changes

Subject	Sleep Angle Change (°/h)	Position shifts per hour	Mean time per position (min)	% Periods Immobility
S01	194(149-274)	1.9(1.1-2.5)	29(23-49)	37(28-50)
S02	193(169-285)	1.9(1.6-2.6)	29(22-37)	34(24-38)
S03	156(128-188)	1.1(0.9-1.3)	46(40-60)	47(43-63)
S04	427(391-566)	3.3(2.8-3.7)	17(16-21)	18(12-23)
S05	374(357-469)	2.8(2.6-3.8)	21(15-22)	23(13-29)
S06	203(168-253)	1.7(1.4-1.9)	34(29-38)	37(29-45)
S07	359(319-402)	2.6(2.3-3.5)	22(16-25)	26(14-32)
S08	261(233-324)	1.9(1.6-2.5)	30(23-34)	37(24-54)
S09	296(238-376)	2.3(1.7-2.9)	25(20-32)	38(23-50)
S10	324(276-392)	2.6(2.5-3.1)	22(19-23)	26(18-37)
S11	274(254-292)	2.3(2-2.4)	25(23-28)	38(32-41)
S12	202(185-211)	1.2(1-1.4)	43(40-52)	54(45-71)
S13	200(190-211)	1.9(1.6-2.2)	30(26-35)	38(19-50)

Values are shown as median(minimum-maximum) of the 4 nights.

Even though the major trends look similar for both indices in Fig. 4, there are also some differences due to the nature of those indices. For instance, the number of position shifts per hour is higher in S13 than S12, while the mean sleep angle change per hour is very similar in both subjects. This means that both experienced an equivalent displacement during the night, but S13 did that while shifting a lot between the 4 classic positions (supine, right, left, prone), while S12 moved the same amount but remaining in a certain position (i.e., without shifting so much to the other sleep positions). This illustrates the advantages of the proposed new high-resolution index. Classical measures, such as 'position shifts', are influenced by the somewhat arbitrary decision of dividing the 360° circle into 4 quadrants, so their values depend on whether the subject crosses the established thresholds (e.g., the supine-to-right border). In contrast, the sleep angle change accounts for the amount of movement without depending on thresholds, as it calculates the average displacement in degrees, regardless of the specific subject position. The higher resolution provided by the sleep angle allows to measure even small changes in intermediate positions, and not only those movements that shift between the 4 classic sleep positions. Consequently, the proposed new index can help to better quantify sleep position changes and assess more accurately sleep position variability.

IV. Conclusion

This study characterizes high-resolution sleep position in a sample of 13 adolescents and investigates its variability over 4 nights. The sleep angle is monitored with a smartphone app that records triaxial accelerometer data. This method allows to reliably measure sleep position in free-living conditions on a multi-night basis, thus facilitating longitudinal sleep studies

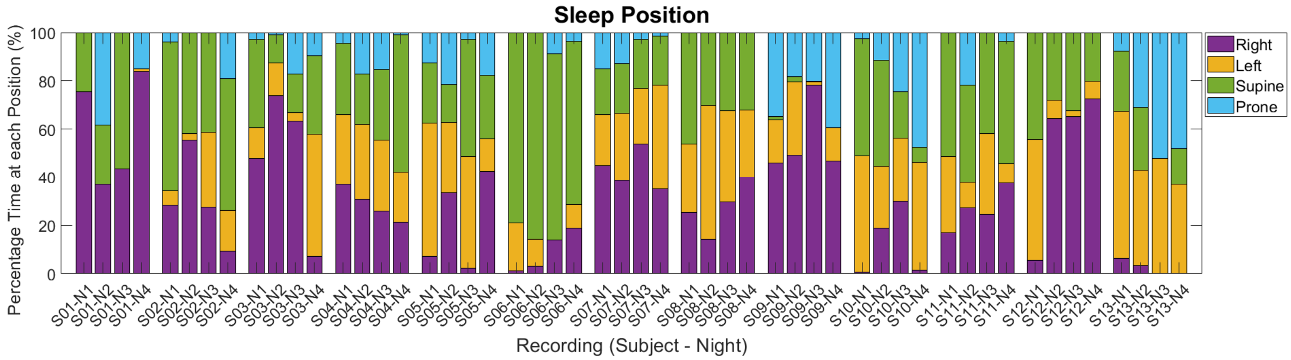

Figure 3. Percentage of time at each sleep position (right, left, supine, and prone) for all subjects across the 4 nights.

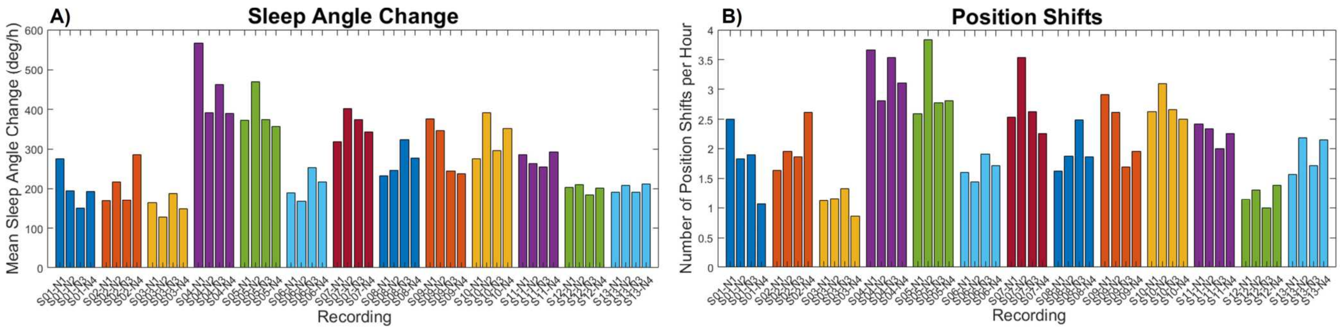

Figure 4. Mean sleep angle change (A) and number of position shifts per hour (B) for all subjects across the 4 nights.

The preferred sleep position in our sample was on the side, while the less common was prone, as in previous studies on adults. Yet, the adolescents experienced more sleep position changes during the night. These findings contribute to increase the body of knowledge on the distribution of sleep positions and nocturnal body movements in the adolescence, supporting the association of these variables with age.

In addition, we proposed a new index, the mean sleep angle change per hour, that has a higher resolution to better quantify body movements and sleep position shifts. This measure does not depend on the thresholds for the classical categorization of sleep position into 4 discrete values (supine, right, left, and prone), as it is based on the sleep angle and thus can account for even small changes occurring at any position.

In future work, the proposed techniques and measures will be applied to longitudinal studies with larger sample sizes and different age groups to further investigate sleep position, nocturnal movements, and other sleep variables, but also their variability and associations with demographics and lifestyles.

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