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Comparison of sleep characteristics measurements: a case study with a population aged 65 and above

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Abstract

Good sleep is crucial for a healthy life of every person. Unfortunately, its quality often decreases with aging. A common approach to measuring the sleep characteristics is based on interviews with the subjects or letting them fill in a daily questionnaire and afterward evaluating the obtained data. However, this method has time and personal costs for the interviewer and evaluator of responses. Therefore, it would be important to execute the collection and evaluation of sleep characteristics automatically. To do that, it is necessary to investigate the level of agreement between measurements performed in a traditional way using questionnaires and measurements obtained using electronic monitoring devices. The study presented in this manuscript performs this investigation, comparing such sleep characteristics as “time going to bed”, “total time in bed”, “total sleep time” and “sleep efficiency”. A total number of 106 night records of elderly persons (aged 65+) were analyzed. The results achieved so far reveal the fact that the degree of agreement between the two measurement methods varies substantially for different characteristics, from 31 minutes of mean difference for “time going to bed” to 77 minutes for “total sleep time”. For this reason, a direct exchange of objective and subjective measuring methods is currently not possible.

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Keywords: Sleep study; sleep quality; PSQI; sleep efficiency

1. Introduction

Sleep is an essential part of our life that, on average, takes up to one-third of every day [1]. Taking care of it is crucial for our health, as sleep is necessary for the recovery of our body as well as the brain. The two main components of sleep are duration and quality. Furthermore, sleep quality can also be seen as a combination of several characteristics

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like the length of time to fall asleep, a number of awakenings at night, etc. [2]. It is known that sleep behavior changes with the age [3]. Among other things, the structure of the sleep stages, sleep efficiency, and sleep duration are typically different for elderly persons compared to younger ones.

In general, methods for measuring sleep quality can be divided into two large groups - subjective and objective measurement [4]. In objective measurement, the values are recorded and analyzed with electronic devices. Different types of sensors and methods for calculating the sleep quality can be used, such as a combination of a triaxial accelerometer and a pressure sensor [5]. In this work, a system was developed that can detect heart rate, breathing, REM/non-REM sleep phases, movement, the position of the person, sleep apnea, and sleep time, and from these data, it calculates the sleep quality with a self-developed algorithm. However, this system uses an accelerometer that has to be placed on the body. This can interfere with normal sleep patterns. The validation of the results by reference measurements was not clearly described in the article. The recognition of breathing rate and movement while sleeping is also one relevant method [6]. For objective measurement of sleep quality, the sensors on the smartphone can also be used as presented in [7]. In this case, three types of smartphone sensors were used: microphone, accelerometer, and light sensor. The smartphone was also used for keeping the sleep diary (derived from Pittsburgh Sleep Quality Index - PSQI [8]). It achieved a 81.48% of accuracy in the classification of "poor" and "good" sleepers. However, using the smartphone to measure sleep quality has some disadvantages, such as the need to place the phone close to the person in the bedroom and increased battery consumption during the night. Moreover, the sensors in different smartphones are not the same, which means that the results may differ between them.

Subjective measurement is based on recording the perceived sleep quality of the subjects. Questionnaires and/or sleep diaries are used [9]. Electronic sleep diaries are often developed as mobile apps. [10] compares a paper-based sleep diary versus an electronic version, and versus a measurement with an actigraph was made. It was concluded that electronic sleep diaries could have an advantage over classic paper-based versions. Another digital sleep diary was presented in [11]. Users perceived the proposed system as practical, but it was found that user experience and motivational effects should be considered when developing the system. In [12] the results of sleep quality measurements were compared with objective and subjective methods, and a correlation was confirmed. However, such important characteristics as "total tome in bed" or "sleep efficiency" were not considered, and the results of some test persons differ significantly so that a combination of the two methods can be useful.

For the detection of sleep disorders (especially insomnias), it is important to pay attention to such sleep characteristics as sleep efficiency, which is also directly linked with sleep duration [13]. Sleep efficiency is defined as the ratio between total time in sleep (sleep time) and the total time in bed (bedtime). It is known that insomnias are more common and sometimes get more distinct in the elderly [14]. Sleep efficiency can be measured objectively (based on electronic device recording) and subjectively (based on the feeling and memory of the person). For the recording of subjective feelings of bedtime and sleep time, the PSQI questionnaire is commonly used [8]. For the electronic measurement, different types of systems can be used, for example, based on the measurement of heart rate, breathing, and movement signals, as described in [15]. In this work, a system based on a multinomial logistical regression approach was developed and tested. The overall achieved accuracy rate is 84% for Wake/Sleep stages, with Cohen's kappa value 0.46.

Several studies targeting the improvement of sleep quality in older adults can be found (e.g., [16, 17]). However, to identify the persons with sleep quality problems and to monitor the progress of therapy, an easy-to-use method for broad application is necessary. Therefore, automatically obtaining the results of measurements, making it possible to test essential sleep characteristics for a high number of older adults could support the enhancement of sleep quality for this age group.

However, the results of measurements with the help of devices and based on the subjective feeling of a person may have some discrepancies [18], which should be investigated to check the possibility of substitution of questionnaires by automatic measurement with the help of electronic devices. Investigation on this question for the subjects from the age group 65+ is the main aim of the study presented in this manuscript.

2. Methodology

2.1. Test subjects

A total of 10 elderly persons (five males and five females) has participated in the study. Nine of them were living in their flats and one in a shared apartment for the elderly. All subjects were over 65 years old with mean value (MV) equal to 72.5 and a standard deviation (SD) of 6.2. The average height of participants was 167.6cm (SD=7.9), and the average weight was equal to 80.8kg (SD=12.6). They were able to carry out the majority of the homework themselves and did not have any severe acute diseases. All participants could understand and respond to the interview questions and were not suffering from advanced dementia. They were given all the study information in advance, and participation was voluntary.

2.2. Measurement methods

For the measurement of sleep characteristics, two approaches were implemented: (1) questionnaire for the measurement of subjective feeling of participating persons, and (2) electronic device for the measurement of sleep characteristics in an objective way.

For the questionnaire-based approach, Pittsburgh Sleep Quality Index (PSQI) was selected [8]. The main reason is that the PSQI is presently the only standardized clinical instrument that covers a broad range of indicators relevant to sleep quality with strong positive evidence for reliability and validity (hypothesis testing) [19]. [20] used the German version of the questionnaire. It asks retrospectively for two weeks about the frequency of sleep-disturbing events, the estimation of sleep quality, regular sleep times, sleep latency and sleep duration, sleep medication intake, and daytime sleepiness. A total of 19 items are used for quantitative evaluation. They are assigned to 7 components, each of which can assume a value range from 0 to 3. The total score results from the summation of the component scores and can vary from 0 to 21, whereby a higher value corresponds to reduced sleep quality. There is an empirically determined cut-off value (of 5), which allows classification into "good" and "poor" sleepers.

Currently, different devices for sleep tracking can be found. Some of them are based on actigraphy [21]; others use piezoelectric sensors [22] or execute analysis of the acoustic signals [23]. For the study described in this document, the Emfit QS+[1] sensor, using a ballistocardiography approach, was chosen [24]. This device can be used for sleep tracking, monitoring general characteristics, like time going to bed, total sleep time, time in bed, and light/deep/REM sleep[25]. It is a contact-free sensor, which can be placed under the mattress to ensure the typical sleep pattern of the users without disturbing their sleep. Furthermore, this device works fully-automatic and does not require any action by the participant of the study other than plugging into a power outlet. This was an essential point for the selection, as one of the study goals is to check if it is possible to execute the measurement of sleep characteristics in an automatic way with a minimal number of necessary actions by users and medical staff. All the data collected with the electronic device can only be accessed by the study organizers.

2.3. Study design

Participants were informed in advance about the procedure of the study. On the first day, the study organizers installed electronic devices in the participants' homes. The Emfit device was placed beneath the mattress across the bed under the chest area according to the device manual. Interviews with general questions (like age, sex, height, weight) were also conducted on the first day of study. The test persons were asked to continue with their regular daily routine and to contact the organizers only in case of troubles. The devices were kept by participants for 14 days, during which time they were visited every 3-4 days to check if everything was going well or if there were problems or questions. On the 15th day, the devices were collected by the study organizers, and the PSQI questionnaires were filled out together with the participants. The measurements were executed for 14 nights, and the questions of subjective measurement were also referred to the same 14 days.

[1] https://www.emfit.com

2.4. Data evaluation

All completed questionnaires were manually processed, and all data were entered into a database. The following sleep characteristics were obtained directly from the questionnaire: time going to bed, sleep onset latency, getting up time as well as total sleep time. PSQI index, total time in bed, and sleep efficiency were calculated according to the guidelines of the German Society for Sleep Research and Sleep Medicine. Calculation of total time in bed:

$$\text{Total time in bed} = \text{getting up time} - \text{time going to bed} \qquad (1)$$

Sleep efficiency (quotient of sleep time and bedtime) was calculated as follows:

$$\text{Sleep efficiency} = \frac{\text{Total sleep time in hours}}{\text{Total time in bed in hours}} \times 100\% \qquad (2)$$

The sleep records created by the electronic device were downloaded using the developer web interface. Time going to bed, total sleep time, and total time in bed is directly available in the overnight recordings. Sleep efficiency was calculated according to Equation 2. In order to obtain results for a period of 14 nights, which are comparable to PSQI, the average values for the mentioned above sleep characteristics (time going to bed, total sleep, total time in bed, and sleep efficiency) for all 14 nights were calculated.

3. Results and Discussion

As several essential sleep characteristics have been measured during the study, the results section will also be divided into six subsections for the detailed presenting of the results. First, the results of two used types of measurements will be introduced: PSQI measurement and measurement with an electronic device (Emfit). After that, several relevant sleep characteristics measured with both measurement approaches will be presented.

3.1. PSQI measurement

Table 1 presents the PSQI measurement results for 10 subjects. The most relevant characteristics for the comparison with a measurement executed by hardware devices are "Time going to bed", "Total sleep time", "Total time in bed" and "Sleep efficiency". PSQI index is used to distiguish poor and good sleepers [8]. According to this approach, subjects with PSQI index higher than five are identified as poor sleepers. Hence, 6 out of the 10 persons who participated in the study have poor sleep quality.

Table 1. PSQI questionnaire results.

Subject	1	2	3	4	5	6	7	8	9	10
PSQI Index	5	4	11	6	3	1	6	6	9	7
Time going to bed	22:00	22:45	21:00	00:00	21:00	22:00	21:00	20:00	00:30	00:00
Sleep onset latency (SOL)	00:15	00:30	01:30	00:10	00:10	00:30	01:00	01:00	01:20	00:10
Getting up time	07:30	07:30	06:30	06:00	07:45	06:30	08:00	09:00	08:00	06:30
Total sleep time (TST)	8:00	7:00	6:00	5:30	9:00	8:00	7:00	8:00	5:30	4:30
Total in bed time (TIB)	9:30	8:45	9:30	6:00	10:45	8:30	11:00	13:00	7:30	6:30
Sleep efficiency (SE)	84%	80%	63%	92%	84%	94%	64%	62%	73%	69%

3.2. Electronic device measurement

The results of monitoring with the Emfit device, used for the objective measurement of sleep characteristics, are shown in Table 2. The comparison of measurement results of this approach with the PSQI questionnaire is presented in the following sections.

Table 2. Electronic device measurement results.

Subject	1	2	3	4	5	6	7	8	9	10
Time going to bed	22:25	22:26	21:13	00:28	20:48	21:22	20:55	20:56	01:18	01:06
Total sleep time (TST)	06:37	08:34	07:50	04:57	09:37	08:30	10:16	10:22	05:20	05:06
Total in bed time (TIB)	07:13	09:37	09:09	05:40	10:41	09:31	11:24	11:21	06:25	05:56
Sleep efficiency (SE)	92%	89%	86%	88%	90%	89%	90%	91%	83%	86%

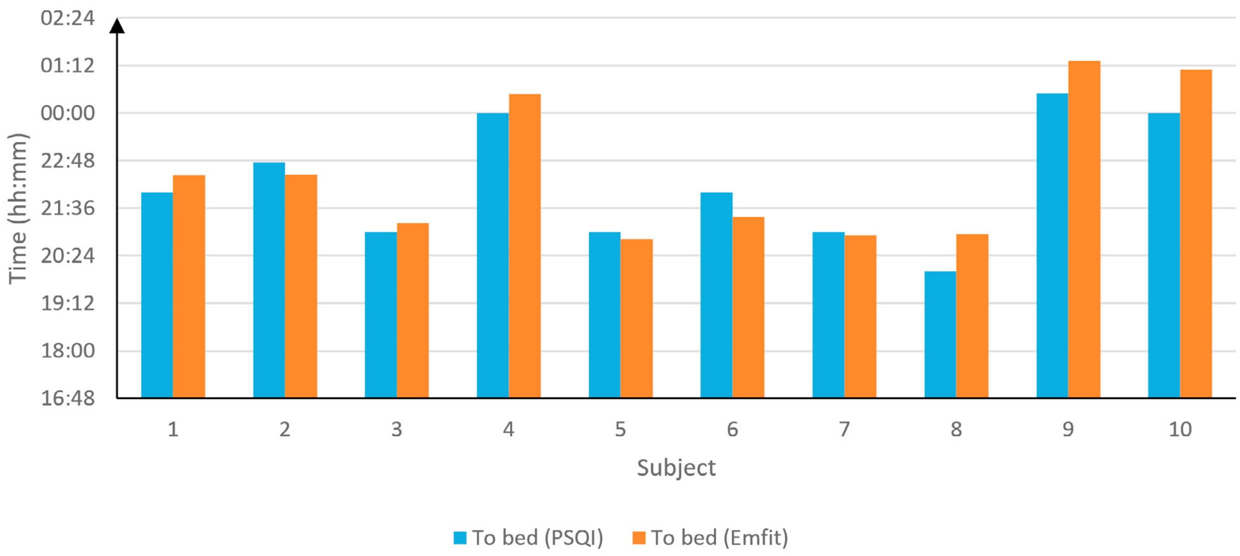

Fig. 1. Average time going to bed.

3.3. Time going to bed

The time going to bed for the ten subjects measured with the PSQI questionnaire and electronic device is presented in Fig. 1. Test persons could indicate the going to bedtimes with very high accuracy, which was confirmed by objective measurement results.

The average deviation of the time going to bed between PSQI and Emfit measurements is 31 minutes.

3.4. Total time in bed

The total time in bed was also estimated very well by the majority of test persons. This can be appreciated in Fig. 2. One of the possible reasons for the bad estimation by subjects 1 and 8 could be that for these two subjects (as well for subjects 2 and 7), records of an electronic device are available for less than eight days of study. Therefore, the calculated average time in bed could differ from the real situation.

The average deviation of this parameter for both measurement approaches is equal to 51 minutes for all subjects and 35 minutes in case subjects 1 and 8 are excluded.

3.5. Total sleep time

Only 50% of test subjects also have a reasonably good estimation of total sleep time. Fig. 3 presents the visualization of this sleep characteristic measurement. These circumstances were also expected because estimating the time spent sleeping is naturally more difficult than total time in bed or going to bed. The availability of a maximum of

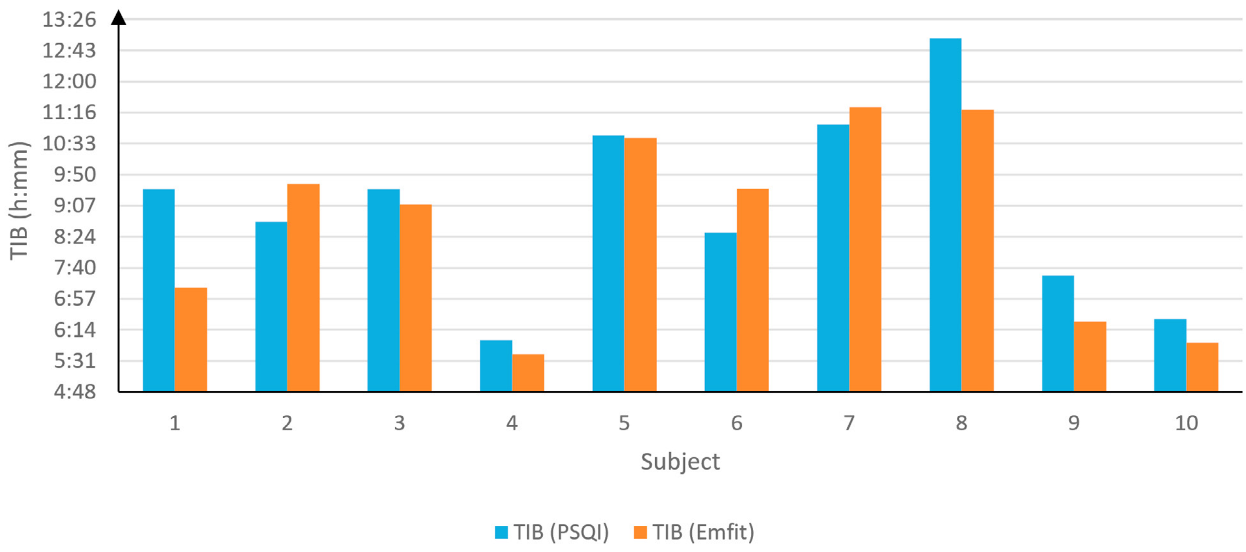

Fig. 2. Average total time in bed (TIB).

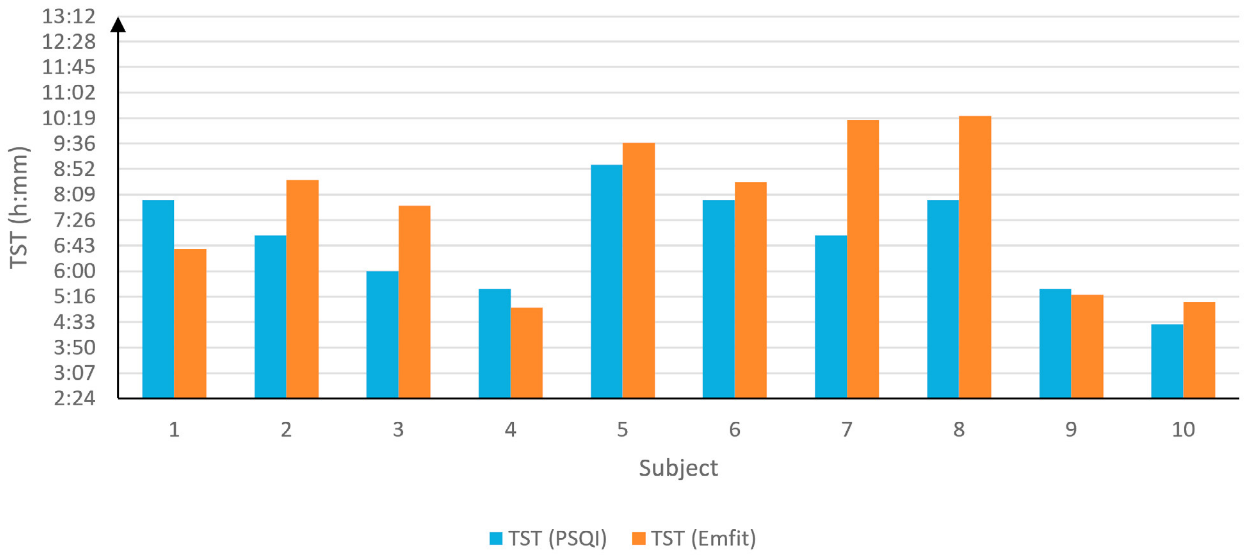

Fig. 3. Average total sleep time (TST).

7-night records (and not all 14) for subjects 1, 2, 7, 8 may have affected the outcome. Nevertheless, the tendency of underestimating the sleep time can be recognized. This fact is also known from other studies [26].

In the case of the total sleep time measurement, the average deviation between objective and subjective measurement is higher than for the previous two sleep characteristics. It is equal to 77 minutes for all subjects, but it is 54 minutes excluding the subjects 7 and 8 from the statistics, because of a lower amount of available Emfit records for these persons.

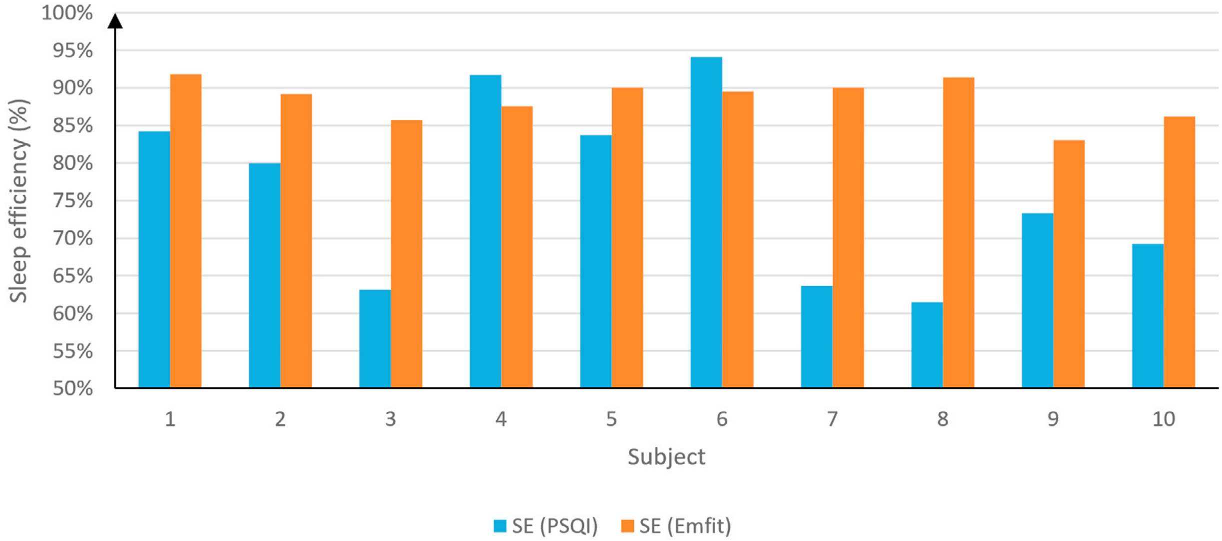

Fig. 4. Average sleep efficiency (SE).

3.6. Sleep efficiency

The presented in Fig. 4 graph of sleep efficiency measurement for both approaches indicates a clear tendency of underestimating this characteristic by the test persons. However, the results of measurement with an electronic device can also be affected by the behavior of test persons – e.g., a continuing lying in bed with no or just a little movement (which can be typical for some persons, especially for less active elderly persons) could be wrongly recognized as sleep by the utilized device.

Comparing the sleep efficiency measured by an electronic device and by PSQI questionnaire, the average deviation between them is equal to 14% for all test persons and 9% in case of exclusion of subjects 7 and 8 for the reasons of missing records for more than the half of nights of the measurement period.

3.7. Comparison of objective and subjective measurement

As seen in previous sections, the results of objective measurements obtained using electronic devices and outcomes of questionnaires based subjective measurements are very similar for some characteristics, but they differ significantly for others. The mean and median deviation between objective and subjective measurement, as well as standard deviation (SD) are presented in Table 3.

Table 3. Difference between objective and subjective measurements.

Characteristic	Mean	Meadian	SD
Time going to bed (hh:mm)	00:31	00:26	00:20
Total sleep time (TST) (hh:mm)	01:17	01:00	00:59
Total in bed time (TIB) (hh:mm)	00:51	00:43	00:40
Sleep efficiency (SE)	14%	9%	10%

4. Conclusions

The study described in this manuscript has confirmed that measurements of sleep characteristics with the help of a questionnaire and electronic devices have a certain level of agreement. However, this level of agreement differs for the particular attribute measured. For example, the time of going to bed can be estimated very well, whereas total sleep time is much more difficult to estimate, as can be seen in Section 3.7.

The main conclusions that have been reached are the following:

- There is a clear tendency of underestimating the total sleep time in case of subjective measurement. Furthermore, the difference between objective and subjective measurement is significant for some subjects, while for others, it is quite small. Therefore, the direct substituting of subjective measurement of this sleep characteristic by an electronic device and vice versa is currently not possible, as the deviation is very person dependent.
- Times of going to bed reported by persons and measured by the device have a high level of accordance. Hence, the conclusion can be done that these approaches are compatible with this type of measurement.
- The correlation of total time in bed measurement using both presented approaches is of a high level with infrequent exceptions. From this, it follows that the subjective one could substitute objective measurement of this characteristic, but only for statistical evaluation of a group of persons and not for a sole subject, as in this case, there is a chance that exactly this person would be the exception case.
- In the case of sleep efficiency, no agreement between the PSQI and the Emfit device measurement was found. One of the reasons is that this characteristic is not measured directly, but calculated from time in bed and total sleep time. Therefore, the imprecisions of both these parameters' measurements are affecting the calculation of sleep efficiency value and result in lower accuracy.

In summary, it can be said that the results of the objective and subjective measurement for the characteristics "time going to bed" and "total time in bed" are very similar, while for "sleep efficiency" and "total sleep time" there are significant differences.

The executed study has permitted to come to the presented above conclusions, but improvements can still be made. First, increasing the number of participating persons could help to achieve more accurate statistical outcomes. For the same reason, the number of nights to be evaluated could be enlarged. Including more devices (based on different technologies) for the measurement could make the outcome more general and less device-dependent. Moreover, of course, separating the test groups in more subgroups (e.g., depending on the age or sex) could provide more targeted results. However, it would be possible only in combination with the first proposed improvement – increasing the number of participants.

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