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Assessment of the replacement of a subjective measurement of sleep-relevant parameters by a measurement with a sensor under the mattress

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Abstract

The influence of sleep on human health is enormous. Accordingly, sleep disorders can have a negative impact on it. To avoid this, they should be identified and treated in time. For this purpose, objective (with an appropriate device) or subjective (based on perceived values) measurement methods are used for sleep analysis to understand the problem. The aim of this work is to find out whether an exchange of the two methods is possible and can provide reliable results. In accordance with this goal, a study was conducted with people aged over 65 years old (a total of 154 night-time recordings) in which both measurement methods were compared. Sleep questionnaires and electronic devices for sleep assessment placed under the mattress were applied to achieve the study aims. The obtained results indicated that the correlation between both measurement methods could be observed for sleep characteristics such as total sleep time, total time in bed and sleep efficiency. However, there are also significant differences in absolute values of the two measurement approaches for some subjects/nights, which leads us to conclude that the substitution is more likely to be considered in case of long-term monitoring where the trends are of more importance and not the absolute values for individual nights.

Keywords: sleep efficiency; sleep study; subjective sleep assessment

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1. Introduction

Numerous scientific studies have shown that sleep is essential to our lives and significantly impacts our health and well-being [1, 2]. It is, therefore, important to maintain a healthy night's sleep, as this can ensure the recovery of a person's mental and physical state [3].

It is crucial to identify the cause early for existing sleep problems and treat it appropriately. To this end, two main groups of methods for analysing sleep to detect possible sleep disorders are objective and subjective [4]. Subjective measurement involves measuring the values the individual perceives, which is usually done using questionnaires [5]. On the other hand, objective measurement is based on electronic devices that measure physiological signals from the human body and allow subsequent evaluation [6]. A classic example of an objective approach is polysomnography (PSG), a standard method that is accurate but time-consuming and expensive [7].

Each of these two approaches has its advantages and disadvantages. Importantly, they are typically used to detect different sleep disorders. For example, sleep apnoea is often diagnosed using objective measures such as PSG or polygraphy [8, 9]. Subjective measures are typically used for some other sleep disorders, such as insomnia [10]. This includes a sleep diary as one of the most commonly used methods. A sleep diary can also be used to monitor and adjust therapy, for example, in the case of cognitive behavioural therapy for insomnia (CBT-I) [11].

Subjective measurement, in the case of the sleep diary, requires daily action by the user. This may lead to a reduction in the number of days on which data are complete, as the user may forget or skip days for other reasons, as has been shown in other studies [12]. Therefore, collecting the required data using an electronic device that collects data automatically could have several advantages, provided that the accuracy of a questionnaire is maintained.

The question of comparing and replacing subjective measurement with objective measurement in sleep medicine, or vice versa, has been the subject of several scientific papers [13, 14]. This could be done, for example, by using a device placed under the mattress, as described in [12]. Other studies have used wearable devices for this purpose [15]. Different devices use different types of sensors and other hardware, the placement can be different, and of course, the signal processing can be very different. Therefore, generalising the results cannot give an accurate answer as to whether a particular device could be used to adequately replace subjective measurement in a particular field of a sleep study. The question of exactly which parameters obtained by subjective measurement should be replaced is also of great importance, and further research in this area is, therefore, essential.

The aim of the research presented in this article is to evaluate the possibility of replacing a sleep diary with a measurement using a device placed under the mattress. The main focus should be on the correlation between the two types of measurement.

2. Methods

Following the defined research objective, the research was carried out to select appropriate methods for subsequent implementation. In this section, a detailed description of the elements that are relevant to the evaluation procedure is given. The 'Methods' chapter has been divided into several subsections according to the aspects covered and to improve readability.

2.1. Subjective measurement

There are several methods of subjective assessment of sleep. For continuous assessment, one of the most common is the use of a sleep diary [16]. Several versions are currently available, including the German version recommended by the German Society for Sleep Research and Sleep Medicine (DGSM) [17], which was chosen for the study. The questionnaire consists of different questions to be completed each evening and each morning. Some examples are taken from [16]:

- What time did you go to bed?
- What time did you try to fall asleep?
- How long did it take you to fall asleep?
- How many times did you wake up, not counting the last time you woke up?

- How long did these awakenings last in total?
- What was the last time you woke up?
- What time did you get up for the day?

Another commonly used tool for subjective measurement is the Pittsburgh Sleep Quality Index (PSQI), which provides a retrospective assessment of sleep over the past four (or in some cases two) weeks.

Based on the answers, several additional sleep-related parameters can be calculated, such as total sleep time (TST), total time in bed (TIB) and sleep efficiency (SE). Sleep diaries play an essential role in diagnosing and monitoring various sleep disorders, such as insomnia [18]. For this reason, the decision was made to use them for the study being conducted.

2.2. Objective measurement

Several types of equipment can be used to measure sleep-related parameters objectively. With the aim of ensuring comfortable use, the device should disturb the user as little as possible during sleep. One option is to use wearable devices that can be comfortably worn on the body [19]. There are several types of wearables, including smartwatches [20]. Another option is to place the device under the mattress, as described in [21]. We have selected EmFit QS+ to perform the objective measurement of sleep characteristics in the conducted study [22].

This choice was made for several reasons. Firstly, this device can be used to measure several relevant sleep parameters such as falling asleep and waking up times (by measuring movement, breathing and heart rates), TIB and sleep profile. The results can be read or exported directly from the web-based application. In addition, this device has been evaluated in several studies to measure sleep characteristics [22, 23]. Settings can be made remotely once using the web interface, so no further action is required before going to bed. The device can be placed under the mattress at chest level and is ready to use once plugged in and connected to the WLAN. As the device also measures respiration and movement signals, it has the potential to detect sleep stages as well, as there are already first evaluated algorithms that enable such detection using these signals [24].

2.3. Sleep characteristics

Subjective sleep measurement usually involves the analysis of several parameters. They are either taken directly from a questionnaire/sleep diary or calculated based on these data. In our experiment, the following relevant parameters were selected to evaluate the possibility of replacing the sleep diary with an objective measurement:

- Total sleep time (TST)
- Time in bed (TIB)
- Sleep efficiency (SE)

These parameters can either be measured directly with the sleep monitoring device or calculated from the measured values. In this way, the set of sleep characteristics used for the evaluation was established.

There are different opinions on the way the SE is calculated, as described in [25], and to avoid possible misunderstandings among the readers of this article, we give the formula used for its computation. In this paper, the SE for the subjective measurement was estimated using the following formula (1):

$$SE = \frac{TST}{(Wake\ up\ Time - Time\ trying\ go\ to\ Sleep)} * 100\% \quad (1)$$

To evaluate the possibility of replacing the subjective measurement with an objective one, we calculated and then analysed the differences between these two types of measurement for each of the selected sleep parameters. The results are detailed and discussed in the Results chapter.

2.4. Experiment design

A total of 11 people took part in the study, of whom two were male and nine were female. All participants were

over 65 years of age according to the inclusion criteria. The mean age was 74.2 years, with a standard deviation (SD) of 5.4 years. The subjects' body mass index (BMI) was 29.7, with an SD of 5.2. All subjects lived at home and had no known acute illnesses at the time of the study.

The study organisers pre-determined the study procedure to ensure a seamless process, and participants were informed in advance about the study procedure. On the first day, the organisers installed and set up electronic sleep monitors in the participants' homes, so the subjects required no further action. An interview with general questions (such as age, sex, height, and weight) was also conducted on the first day of the study, and any questions about the study were answered. Subjects were asked to continue their usual daily routine and to contact the organisers only if they had any problems.

The devices were kept by the participants for 14 days, during which time they were visited every 3-4 days to check that everything was going well or if there were any problems or questions. The under-mattress device had to remain plugged in at all times, or at least plugged in no later than 20 minutes before going to bed and plugged out no earlier than 20 minutes after getting up.

On the last day, the study organisers collected the devices and the PSQI questionnaires were completed with the participants for the period of two weeks. For comparability, measurements were taken over 14 nights, and the subjective measurement questions also referred to the same 14 days, leading to obtaining a set of 154 overnight recordings for the evaluation procedure.

3. Results

In order to answer the open research questions, the study was conducted according to the defined design. To achieve this, obtaining a significant number of night recordings for subsequent analysis was necessary, and this was achieved with a total of 154 recordings (11 subjects each two weeks).

In general, both the device under the mattress and the questionnaire were well accepted by the users, with feedback regarding the device that some subjects even forgot that there was a device taking a measurement.

The absolute values of the differences between subjective and objective measurements were calculated for the three planned parameters (TST, TIB and SE) per subject. The results were prepared as diagrams to achieve better comprehensibility, e.g. TIB measurement is presented in Figure 1.

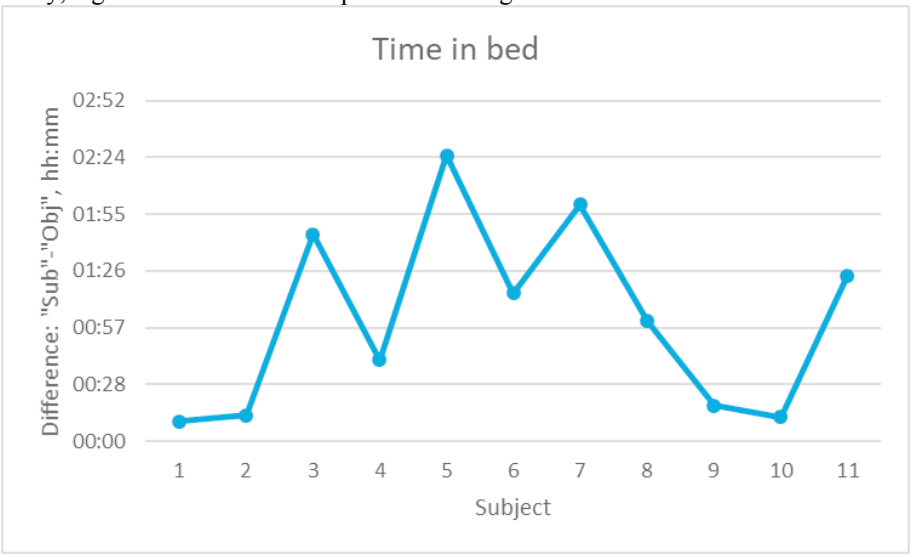

Fig. 1. Absolute differences between objective and subjective measurement for TIB for every subject.

Figure 1 illustrates that for more than a third of the subjects, the difference between the two types of measurement is relatively small, less than 20 minutes, but for two subjects, the difference is 2 hours or more. These more significant

differences may be explained by the fact that the subjective measurement with the PSQI questionnaire is a retrospective two-week survey, and as some people's bedtimes can vary significantly between weeks, this may be reflected in the findings.

The measurement of differences for TST is presented in Figure 2.

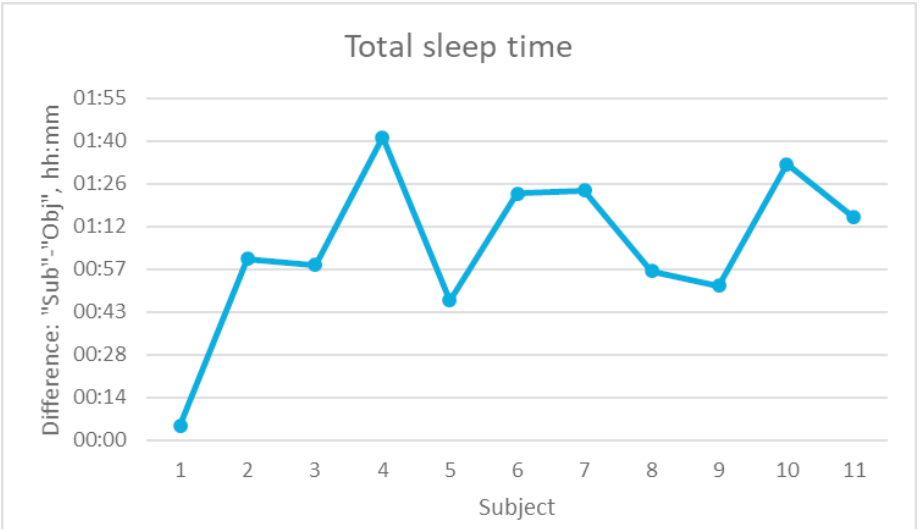

Fig. 2. Absolute differences between objective and subjective measurement for TST for every subject.

It can be seen that for the absolute majority of subjects, the difference is relatively stable between 47 minutes and 1 hour 33 minutes. The discrepancy between subjective and objective measurement is typical for this parameter, as several aspects are not perceived in the subjective measurement, such as waking up during the night. It is also problematic to remember the exact time of falling asleep, as it is impossible to fall asleep and look at the watch simultaneously. Furthermore, it is vital in the subjective measurement not to look at the watch too often when trying to fall asleep.

Figure 3 provides a visualisation of the absolute differences between the two types of measurement for SE.

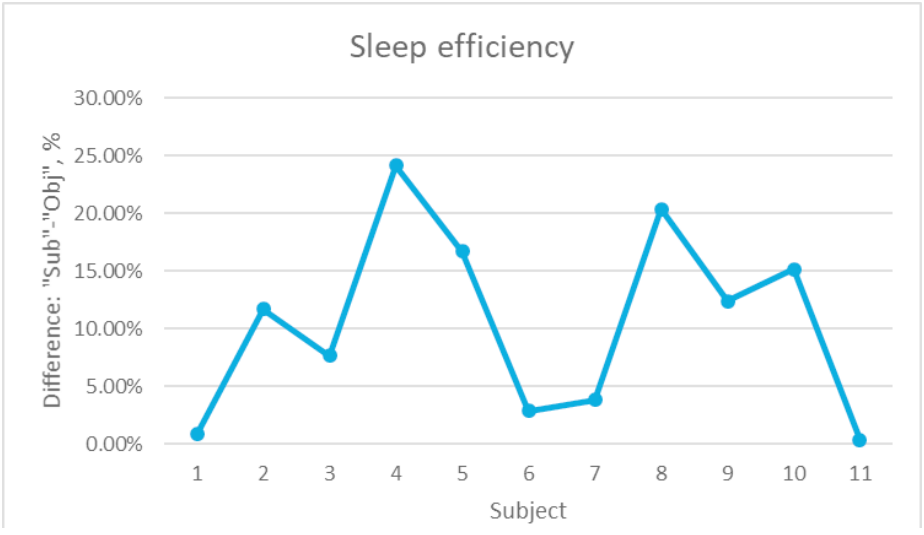

Fig. 3. Absolute differences between objective and subjective measurement for SE for every subject.

It can be seen that there is a considerable variation in the differences. This is partly due to the fact that SE combines TST and time spent trying to fall asleep, which leads to more variability in the results due to multiple components.

In order to provide a shorter and clearer summary, we have visualised the results for each sleep parameter in Figures 4 and 5 using box plots.

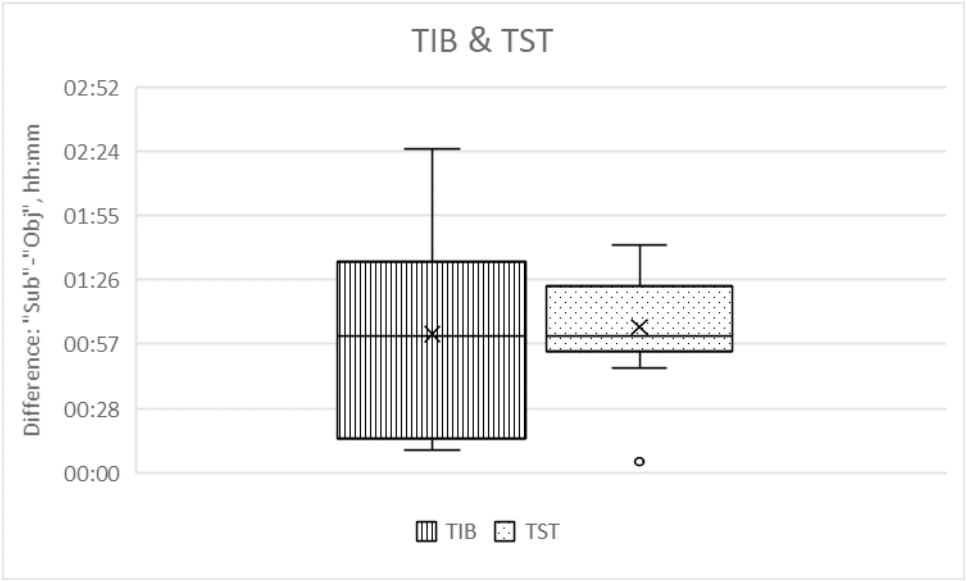

Fig. 4. Box plot with absolute differences between objective and subjective measurement for TIB and TST.

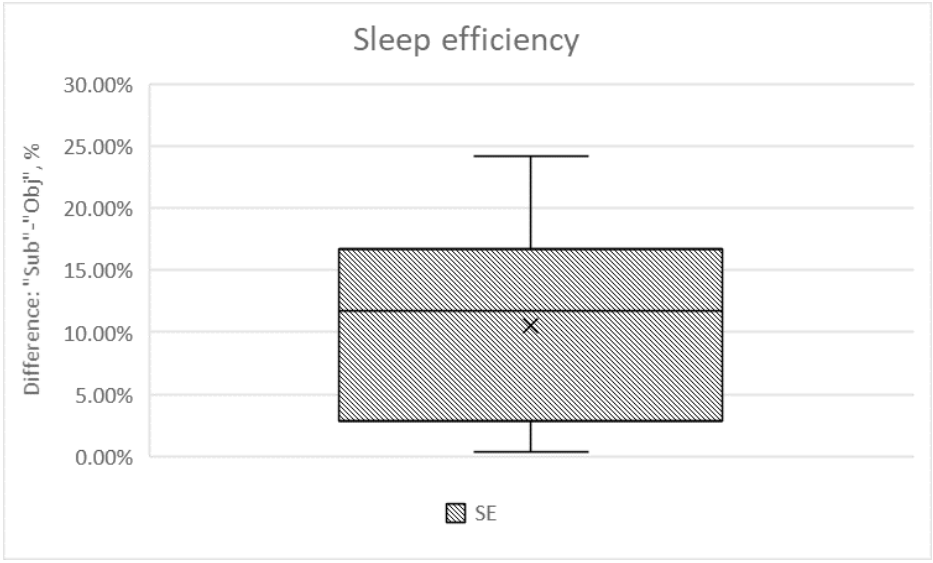

Fig. 5. Box plot with absolute differences between objective and subjective measurement for SE.

In order to summarise the main results of validating the possibility of substituting a subjective measurement with a measurement employing a sensor placed under the mattress, the relevant statistical values for all three selected sleep characteristics are presented in Table 1.

Table 1. Statistical analysis of the differences between subjective and objective measurement.

Sleep characteristic	Mean	Median	Standard deviation
Time in bed (hh:mm)	01:02	01:01	00:47
Total sleep time (hh:mm)	01:05	01:01	00:26
Sleep efficiency (%)	10.6%	11.7%	8.1%

The results presented above concern the absolute values of the differences between the two measurement approaches. However, the question of whether subjective or objective measurement overestimates the parameters is of great research interest. For this reason, Table 2 also includes this feature for all participants additionally to the summary of calculated values of differences between subjective and objective measurement of sleep relevant parameters.

Table 2. Difference between subjective and objective measurement, including its "direction".

Sleep characteristic	Subject										
	1	2	3	4	5	6	7	8	9	10	11
Time in bed (hh:mm)	**00:10**	*00:13*	**01:45**	**00:41**	**02:25**	**01:15**	**02:00**	**01:01**	**00:18**	*00:12*	**01:24**
Total sleep time (hh:mm)	**00:05**	*01:01*	**00:59**	*01:42*	**00:47**	**01:23**	**01:24**	*0:57*	*00:52*	*01:33*	**01:15**
Sleep efficiency (%)	*0.8%*	*11.7%*	*7.6%*	*24.2%*	*16.7%*	**2.9%**	*3.8%*	*20.4%*	*12.4%*	*15.2%*	**0.4%**

Values in bold mean that the values obtained by subjective measurement are higher than those obtained by objective measurement. Values in italics mean that the subjective measurement underestimates this parameter compared to the objective approach.

We can recognise that the time in bed is overestimated by subjective measurement for most subjects, and the difference is minimal for only two subjects where this parameter is underestimated. Differences between two measurement approaches are also known from other studies [26]. In the case of total sleep time, there is no clear tendency for overestimation by either approach, as the variability is very high.

When analysing the values obtained for sleep efficiency, there is clear evidence that this parameter is often underestimated when filling in the questionnaire.

4. Conclusions

The conducted study made it possible to discuss several issues related to the comparison between an objective measurement with a device that can be used comfortably under the mattress and a subjective measurement. In conclusion, the following main aspects can be highlighted:

- The correlation between subjective and objective measurements of total time in bed, total sleep time and sleep efficiency is present.
- There is a clear tendency for sleep efficiency to be underestimated by the subjective measurement among the study participants
- Time in bed is significantly overestimated
- Incomplete or missing night recordings could partly explain outliers for some of the subjects.
- Based on the results of this and other studies conducted, the possibility of interchanging two methods (objective and subjective) seems realistic, especially for long-term monitoring when not absolute values but trends are of interest.

The performed study has, however, several limitations:

- A specific hardware device was evaluated. A generalisation of the results to all automatic sleep monitoring devices is, therefore, not possible due to possible differences in hardware and software components.
- The age of the participants was limited to 65+ years to obtain statistically significant results for this specific age group. Therefore, the results obtained are also limited to this age group, and the findings cannot be said to be transferable to those of other ages.
- In the study conducted, the experiment was carried out with 11 subjects over two weeks, resulting in a total of 154 overnight recordings. This number of recordings can provide statistically relevant results. However, if the sample size could be increased, the transferability of the results to the whole population would be of higher accuracy.
- In setting the study's objective, the decision was made to analyse three sleep characteristics: Sleep Efficiency, TST, and TIB. Of course, the results obtained in the research conducted cannot be extrapolated to others. They are limited to the studied characteristics due to the specificities of measuring the different parameters. Naturally, several additional parameters can still be objectively and subjectively measured and could have a different correlation.
- Moreover, in the analysis carried out, the PSQI was chosen as the instrument for subjective measurement. However, this questionnaire summarises the values for the entire period of two weeks without providing daily measurements. Other tools, such as a sleep diary that provides data for each day, could increase the accuracy and granularity of the results. Furthermore, daily filling out would decrease the affect of "forgetting" some values.

According to the obtained outcomes, at this moment, no general recommendation for substituting sleep diary measurement with an objective approach using a placed-under-mattress sensor can be made based on the evaluation performed, and the further investigation appears to be of importance.

Based on the gained experience and to improve the scientific significance of the research, several directions of future work were determined:

- Subsequent studies with a larger number of test subjects are in planning.
- In addition, other age groups are to be included in the experiment to increase the generalisability of the results.
- The set of sleep characteristics for evaluation is also to be expanded. For example, wake-after-sleep onset (WASO) or sleep quality could be included in future studies to provide comprehensive research results.
- Applying a sleep diary as a subjective measurement tool is planned to provide more precise daily results, which should increase the accuracy and ability to evaluate both measurement methods daily.
- There is a plan to conduct a study with other types of electronic devices (separately or in combination, e.g. with a wearable/smartwatch) to compare measurement results. This could allow conclusions to be drawn about whether there are significant differences in the results when a different type of device is used for the objective measurement.

In general, the topic of replacing subjective measurement with objective measurement shows potential for increasing comfort and simplifying the tracking of changes in sleep patterns over longer periods of time.

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