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Comparison of Two At-Home Sleep Monitoring Technologies

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Abstract

Background: Despite the importance of regular sleep patterns being well-known throughout society, a growing number of people claim to be sleep-deprived. There is a need to identify a simple and unobtrusive method in which people can accurately track their sleep to monitor changes and track how their sleep affects their daytime function. **Methods:** Here, we compared two at-home sleep monitors, the Zeo EEG headband system and the OURA physiological ring, in twenty-seven healthy young adults to determine their relative accuracy in classifying the various sleep stages. The two devices track sleep differently. The ring relies on hand movements and hemodynamic and respiratory changes in the body, while the headband system analyzes forehead EEG brain activities. Subjects wore both devices to sleep for 3-5 nights. Total sleep time, latency to sleep, time in wake, percentage and time in REM, percentage and time in light sleep, and percentage and time in deep sleep were recorded. The means and mean standard deviations of the two systems' sleep variables were assessed. **Results:** Compared to the EEG headband, the ring overestimated the awakening episodes' duration and underestimated the sleep latency. The ring was also more variable in capturing the total awakening episodes and deep sleep duration. Notably, the EEG headband gave information about the number of awakenings, which the ring does not report. **Conclusion:** Sleep quality, or the lack thereof, has relevant applications in physical rehabilitation. The results of the study point to the need to continue developing reliable and simple methods to monitor night sleep quality. While this study looked at individuals who do not have sleep dysfunction, it is possible that the discrepancies between the two sleep monitoring systems would be wider among people with sleep disorders.

Keywords: accelerometer, actigraph, EEG, OURA, ring, sleep, technology, Zeo

Introduction

Humans spend, on average, one-third of their lives asleep, with adults sleeping 7 to 8 hours each night. Sleep can be measured through electroencephalography (EEG). It records brain electrical activities from electrodes that are placed on the scalp. The electrical activities are used to estimate the various sleep cycles and awakening episodes. Polysomnography (PSG) is an overnight sleep test in which brain activities, oxygen levels in the blood, heart rate, breathing rate, and eye movement are recorded during sleep. This enables sleep stages and cycles to be accurately classified and monitored and identify sleep pattern disruptions, including awakening episodes. While PSG may yield accurate results and can help correctly identify sleep disorders and disruptions, it is expensive and burdensome, requiring an overnight stay at a hospital and a subsequent return visit to get the results. It is, therefore, typically not administered unless the individual notices a change in their daytime function or a symptom that could be associated with disruption of their normal sleep.

PSG also does not allow individuals to track changes in their sleeping patterns to gauge improvement and increase in the quality of their sleep. Consequently, a need for an at-home device that people can use daily to track their sleep persists. There is market demand to identify a simple and unobtrusive method in which individuals can accurately track their sleep to monitor changes and track how their sleep affects their daytime function, such as alertness,[1] cardiovascular well-being,[2,3] mental health,[4] and memory.[5,6]

Here, we compared the EEG sleep monitor (marketed as *Zeo*) against the physiological-based *OURA* monitor. The Zeo is a validated, unobtrusive, easy, and convenient dry wireless 2-channel EEG system.[1,2] The monitor is a sport-like adjustable headband with a lightweight rechargeable battery lasting 16 hours on a full charge. It measures brain waves through the frontal regions (Fp1 and Fp2).[3] The Zeo has been shown to have excellent overall agreement in scoring the various sleep states compared to the gold standard described by Rechtschaffen and Kales in 1968.[4,5] The validity of the Zeo sleep monitor in scoring the various sleep stages has been compared to full polysomnography in a sleep laboratory. The percent agreement between the two methods ranged between 74.7% and 95.8%.

The OURA sleep monitor is a ring worn on the finger. Unlike the Zeo, it uses a different methodology to capture sleep. Its technique appears comprehensive; it uses a combination of accelerometer, temperature, and infrared technologies to measure blood volume pulse (BVP) using infrared LEDs, a 3D accelerometer and gyroscope, and a heat sensor. From these measurements, it estimates heart rate, respiratory rate, and heart rate variability.[6] A study by de Zambotti et al. looked at the ring and compared its effectiveness as a sleep tracker to PSG. The study recruited 41 adolescent and young adult subjects. Subjects were observed in a single night in a laboratory using the ring and standard PSG protocol. Data was compared using Bland-Altman plots and epoch-by-epoch (EBE) analysis. It was found that the ring underestimated stage N3 sleep compared to PSG and overestimated REM sleep. Both differences were within the ≤30 min a-priori-set clinically satisfactory ranges for at least 85% of the population. The EBE analysis found the ring to have a 96% sensitivity to detect sleep; however, the specificity to detect waking was 48%.[7]

Although these results suggest that the ring holds promise for conveniently tracking sleep, data was obtained from only one recording night. For relative reliability in sleep data, it would be essential to determine how consistent the ring is in capturing multiple sleep sessions and compare it with the EEG sensor technology.

Methods

Subjects

Healthy subjects were recruited based on convenience sampling from Augusta University in Augusta, GA, USA. Twelve men and fifteen women, with a mean age of 26.5 (+/- 3 years), participated in this study, which was approved by the institutional review board. All subjects signed an informed consent form before participating in the study. Exclusion criteria included any known diagnoses of sleep disorders and any known allergies to skin adhesives.

Procedures

Two devices were used to collect data in this study. The first device was the Zeo headband device, which uses EEG to detect sleep phases and is a verified method of monitoring sleep phases. The electrodes are embedded in the headband worn on the forehead. Sleep classifications are calculated from the EEG signals in one-minute intervals. There is no significant preparatory work or messy clean-up afterward. Numeric and graphical results are automatically generated, which provide sleep details, including time to fall asleep (latency), number of times awoken during sleep, and durations of REM, deep, and light sleep. Sleep efficiency (refreshing versus disruptive sleep) is then derived.

The second device was the OURA ring. It is a new technology that measures hemodynamic changes, including heart rate, body temperature, heart rate variability, and blood flow, to track sleep. The website does not specify the algorithm used to calculate the data for each outcome measure that is similar to what the EEG headband system is measuring. Calculations are stated to be based on research. The ring uses photoplethysmography (PPG), which is a form of recording blood volume pulse optically. It is similar to pulse oximeters used in the hospital setting, using a proper LED and photo receiver. This infrared light travels deeper into the skin than other wavelengths, providing a more accurate reading. This measurement form captures the inter-beat intervals (IBI), meaning the peak blood volume signals a new heartbeat. The ring system calculates heart rate variability (HRV) during the night using the rMSSD formula (root mean square of the successive differences). It tells how much variation is in the heartbeats within a time frame – in the case of the ring, it is five minutes. The website claims that calculations of this information have been performed in such a way that it filters out potential inaccuracies.[6]

Each subject wore the two sleep monitors at home for 3-5 nights. They were instructed not to consume caffeine or alcohol after dinner, nap, or be exposed to excessive stress, leading to sleep deprivation. Subjects were asked to wear the EEG headband and ring simultaneously each night. They were instructed to wear the devices only to sleep until they woke up in the morning, concurrently removing both devices from their body. Subjects were to keep the devices on during any awakenings at night, including while using the restroom. The following restrictions were given to the subjects: no alcohol intake before sleep, no caffeine intake before sleep, no naps during the day, and getting at least 7-8 hours of sleep each night. The appropriate size ring was given to each subject for use during the study. The ring could be worn on any digit but was required to fit the digit snugly. Each subject was given a demonstration of the equipment before the start of the study. Data was retrieved from each subject daily during the study to ensure the devices worked appropriately. Subjects were asked at the end of the five days whether they engaged in the activities they were instructed to abstain from.

Data Analyses

The outcome measures collected from the subjects included duration of total sleep duration, time in wake (during awakening episodes), latency to sleep, duration of deep sleep, duration of REM sleep, and duration of light sleep. The frequency of awakenings was a critical variable, but we could not analyze it because the ring software stopped reporting the data while the study was ongoing. We will reflect on this topic in the Discussion section.

The means and mean standard deviation of the various outcome measures of the two systems were analyzed using the multivariate Hotelling's T^2 two-sample paired test and 2-tailed univariate tests following a significant outcome (paired t-tests). Alpha was set at 0.05.

Results

Comparison of the Means

To investigate whether the ring and EEG headband sleep monitoring devices differed, a multivariate Hotelling's T^2 two-sample paired test was performed on the mean measures with total Z (total sleep), latency, wake, REM, light, and sleep as dependent variables. The correlation among the variables ranged from r=0.02 to 0.55. The main effect was significant, $T^2 = 56.82$, $F(6, 22) = 7.72$, p=0.00015. Follow-up univariate analyses revealed that the ring device overestimated time-in-wake (189%, p = 0.00004) and light sleep (22% p = 0.0002) and underestimated latency to sleep (-47% p = 0.004), deep sleep (-23% p = 0.005) and REM sleep (-19% p = 0.013). Univariate results and the magnitude of difference between the devices are found in Table 1.

Table 1. *Comparison of Means between the OURA ring and Zeo EEG headband*

Variable	n	Ring	EEG	**Diff
Time in Wake (awakenings)	27	37 (22)	13 (20)	*189
Latency to Sleep	27	10 (6)	20 (15)	*-47
Total Sleep Time	27	408 (43)	401 (60)	1.8
Duration of Deep Sleep	27	64 (32)	83 (27)	*-23
Duration of REM Sleep	27	94 (40)	116 (34)	*-19
Duration of Light Sleep	27	246 (58)	202 (43)	*22

Note. Values are mean ± SD, Variable (minutes), Diff (%); Ring = OURA Ring, EEG – EEH Headband, Diff = Difference
**p<0.01. Results of univariate paired t-tests following a significant multivariate Hotelling's T^2 two-sample paired test. The ring overestimated time-in-wake and light sleep and underestimated latency to sleep, deep sleep, and REM sleep. The frequency of awakening episodes was not available for analysis (see Discussion).*
***Difference formula is based on ((Ring – EEG) / EEG) x 100%.*

Comparison of the Variability

The ring and EEG headband sleep monitoring device variability (i.e., standard deviation) were analyzed. The correlation among the variables ranged from r=0.04 to 0.64. The main effect was significant, $T^2 = 75.25$, $F(6, 22) = 10.22$, $p = 0.00002$. Follow-up univariate analyses revealed that the ring was more variable in time-in-wake (102%, $p = 0.003$) and deep sleep (59%, $p = 0.0003$). Univariate results and the magnitude of difference between the devices are summarized in Table 2.

Table 2. *Comparison of Variability between the OURA ring and Zeo EEG headband*

Variable	n	Ring	EEG	**Diff
Total Sleep Time	27	49 (5)	65 (8)	-25
Duration of Deep Sleep	27	23 (1)	14 (1)	*64
Time in Wake (awakenings)	27	14 (2)	7 (1)	*100
Latency to Sleep	27	6 (1)	10 (2)	*-40
Duration of REM Sleep	27	31 (3)	34 (4)	*-9
Duration of Light Sleep	27	47 (4)	45 (4)	*4

Note. Values are mean standard deviation ± SD, Variable (minutes), Diff (%); Ring = OURA Ring, EEG – EEH Headband, Diff = Difference
**p<0.01. Results of univariate paired t-tests following a significant multivariate Hotelling's T^2 two-sample paired test. The ring was more variable in time-in-wake (102%) and deep sleep (59%). Variability in the frequency of awakening episodes was not available for analysis (see Discussion).*
***Difference formula is based on ((Ring – EEG) / EEG) x 100%.*

Discussion

Discrepancies between the ring and EEG headband devices

The most significant discrepancy between the ring and the EEG headband was the ring's overestimation and higher inconsistency in classifying wake time. A possible reason could be that the ring interprets a subject's movements during sleep, particularly during the light sleep phase, as an awakening. Likewise, recording movements of the hand by the ring may have produced an underestimation of the sleep latency. If a subject remains motionless while trying to fall asleep, the ring may incorrectly classify the person as falling asleep, thus producing the overestimation.

The ring was also found to overestimate deep sleep and REM sleep compared to the EEG headband system. There is inhibition in the corticospinal pathway during these two sleep phases, causing one's muscles to become essentially paralyzed in people without sleep dysfunction.[8] The ring may have relied on physiological measures rather than its accelerometer to estimate these two outcome measures, contributing to the underestimation.

In terms of consistency, the ring's higher variability in measuring deep sleep could be due to the limitation of the physiological parameters that it uses. The higher variability in measuring the time spent in wake could be due to the same reason postulated earlier regarding the reliance on movements of the hand wearing the ring.

Frequency of Night Awakenings as a Measure of Sleep Quality

In addition to inadequate sleep, another critical factor in the assessment of night sleep quality is sleep fragmentation, which includes frequency of awakenings.[7–10] Longer and irregular awakenings during sleep have been shown to decrease sleep quality and possibly interfere with cognitive processes.[9] Unfortunately, the ring system did not report the frequency of awakening episodes due to an update in the software while the study was underway. In contrast, the EEG headband system did provide this information. In subsequent updates of the ring's software, the number of night sleep awakenings was no longer included explicitly in the summary report. The graphic display still shows whether the user awakens during the night, but it is unknown how long the user must be awake for it to be reported. A representative of the ring company clarified that the information was removed from the summary report so as not to "cause any stress" to users and wanted to "highlight the restfulness" instead. As a result, we could not include this important outcome measure in the statistical analyses.

Implication of decreased sleep quality on physical therapy practice and public health

A chronic decrease in sleep quality, whether due to sleep deprivation or fragmentation, can affect effective physical therapy practice and public health in several ways:

1. Impaired Physical Function and Performance. Decreased sleep quality can affect postural control, coordination, and reaction time. [11] Physical therapists may find it more challenging to perform exercises and rehabilitation activities safely and effectively with patients.
2. Increased Risk of Injury. Decreased sleep quality increases the risk of injury due to impaired cognitive and motor functions.[12] Physical therapists must be vigilant when working with patients during exercises and other physical activities.
3. Impaired Immune Function: Decreased sleep quality disturbs the immune system, which may lead to a risk of infectious diseases and other health problems.[13] This

increases the physical therapist's burden of care and treatment of patients.

4. Increased Risk of Chronic Conditions: Decreased sleep quality is associated with an increased risk of chronic conditions such as obesity, diabetes, and cardiovascular disease.[14,15] These can significantly affect public health by making access to physical therapy treatment more difficult. They also jeopardize treatment outcomes.

5. Impaired Mental Health: Decreased sleep quality affects mental health, including increased anxiety, depression, and mood. [16] Physical therapists may find that these mental issues confound their ability to engage patients in therapy effectively. Patients may also not be able to comply with treatment plans.

Recommendations for policymakers, researchers, users of sleep devices, and the general population

1. Policymakers. Policymakers should hold public education on the importance of sleep quality as a high priority. Policies should be implemented to encourage and support healthy sleep habits. They include guidelines for school start times, workplace policies that consider sleep health, and increased funding for sleep research.[17,18]

2. Researchers. The mechanisms of sleep continue to be an area that needs to be investigated; new diagnostic and tracking tools need to be developed; the effects of decreased sleep quality on non-healthy populations, as well as exploring the use of behavioral interventions to improve sleep, etc., remain important topics of research.[16,17,19]

3. Users of sleep devices. It is essential that users of sleep monitoring devices appreciate the limitations of sleep devices and not rely solely on them to assess their quality of sleep. It is also important to use these devices with healthy sleep habits, such as maintaining a consistent sleep schedule and avoiding electronic devices before bedtime.[20]

4. General population: The general population should prioritize healthy sleep habits, such as getting enough sleep each night, maintaining a consistent sleep schedule, and creating a sleep-conducive environment in their bedroom.[21,22] It is also important to seek medical help if experiencing persistent sleep problems or symptoms of sleep disorders.

Conclusion

Overall, the ring system does not appear to provide a level of accuracy and consistency compared to the EEG headband. These devices track sleep differently. The ring system relies on hand movements and hemodynamic changes, while the EEG headband system relies on frontal EEG. Additionally, the ring system no longer reports the number of episodes of awakenings, thus missing an important piece of information about sleep dysfunction. Sleep quality has significant implications for physical therapists and clinical practice in general, so more reliable and simple sleep monitoring devices, like the ring system, should be developed. This study only looked at individuals who do not have self-reported sleep dysfunction. Further research should be conducted to compare the ring's ability to track sleep stages to the EEG headband monitoring system in people with sleep disorders. It is possible that the discrepancies between the two sleep monitoring systems would be more pronounced in people with sleep dysfunction that produces increased body movements.

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