White Paper

Polar Sleep Plus Stages

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1 Introduction

Sleep is vital to overall health and well-being. It plays a critical role in cardiovascular, immune, hormone, and brain functions, as well as metabolism and appetite regulation.[1] Even though most people acknowledge that sleep is important, many simply sleep too little. Over time, insufficient sleep increases the risk for several chronic health problems, including cardiovascular disease, obesity, diabetes, and depression, to name a few.[1]

Moreover, adequate recovery is an integral component of the training process and performance development in athletes. Sleep has been recognized as an effective recovery strategy.[2,3,4,5] It is fundamental for both physical and mental restoration. Several hormonal responses relating to physical restoration take place during sleep. Sleep is also the time when a number of processes linked to memory, learning, cognition, vigilance, mood, and motivation occur.

For athletes, sleep loss can hinder training adaptation. It's been proven that total sleep deprivation negatively affects exercise performance. However, the scope of the effects of partial sleep restriction is a more conflicting topic.[6] The extent, influence, and specific mechanisms of sleep loss affecting exercise have remained unclear. On the other hand, the adverse effects of sleep loss on cognitive performance are clear: inadequate sleep can impair performance in sports that require high levels of cognitive functioning.[6]. As a result, the success of a personal training plan also depends on adequate sleep and recovery. For instance, lack of sleep may increase the risk of injury and illness, and thus, reducing participation in planned training.[2]

Despite the importance of sleep, athletes are often unable to achieve the recommended amount of sleep during training or competition periods. [2,4,5,6] Factors known to negatively affect sleep include competitions, early morning training, increased training load, travel, jet lag, and altitude. There is growing evidence that increased sleep duration and improved sleep quality are associated with better performance and greater competitive success.[2,3] Thus, athletes may benefit from optimizing and extending their sleep.

This paper describes Polar's Sleep Plus Stages feature. The patents EP3366206, US10993656, and CN110366387 are related to this feature. Sleep Plus Stages complements Polar's previous sleep analysis by adding data on sleep stages and a sleep score—a single number that provides a quick summary of sleep duration and quality. This automatic sleep measurement allows for regular sleep tracking, helping monitor long-term sleep habits and identify factors that may affect sleep.

2 Background

Both the amount and quality of sleep can be assessed using objective metrics. The most common methods to assess sleep in scientific and

clinical practice are polysomnography, accelerometry, and questionnaires. While polysomnography remains the 'gold standard' for assessing sleep, accelerometry appears to be the preferred method for athletes.

2.1 Polysomnography

Polysomnography is an expensive method that requires specialized laboratory equipment, making it impractical for regular tracking. It measures brain activity, eye movements, and muscle activity using surface electrodes attached to the head. Based on these signals a sleep technician classifies each 30-second epoch of sleep into different sleep stages according to the American Academy of Sleep Medicine (AASM) rules. The sleep stages are visualized as a hypnogram, a graph representing the sleep stages as a function of time. A typical night's sleep is composed of roughly 90-minute cycles divided into periods of rapid eye movement sleep (REM) and non-rapid eye movement sleep (non-REM).[7] Non-REM sleep is further divided into three stages that differ in terms of depth of sleep.

Light sleep

Light sleep refers to the two lightest stages of non-REM sleep, corresponding to N1 and N2 according to AASM classification. When we fall asleep, we first enter the lightest stage of sleep and then proceed to other sleep stages. Adults spend about half or more of the night in light sleep. This stage of sleep is thought to play a role in memory consolidation.

Deep sleep

The deepest stage of non-REM sleep is often called deep sleep or slow-wave-sleep, corresponding to N3 according to AASM classification. Deep sleep is considered the stage during which the body actively repairs and restores itself. For that, the pituitary gland releases growth hormone during this sleep stage. This hormone is necessary for muscle growth, repair, and bone building—all essential to athletic recovery following exercise. Deep sleep also promotes the right balance between anabolic and catabolic hormones, accelerating muscle adaptation and growth. In addition, deep sleep supports the immune system and influences certain aspects of memory and learning.

REM sleep

As deep sleep restores the body, REM sleep is considered to restore the mind. REM sleep is characterized by vividly recalled dreams and rapid eye movements. During this stage, brain activity is quite similar to that during waking hours. It has been proposed that this high brain activity is associated with memory consolidation and the learning of motor skills. Thus, both non-REM and REM sleep are fundamental for training adaptation and maintaining proper physical and cognitive function during exercise performance.

2.2 Sleep amount

The National Sleep Foundation (NSF) provides practical recommendations for daily sleep duration across different age groups.[8] The recommended daily sleep duration for healthy adults is between 7 to 9 hours. On average, this amount of sleep on a regular basis is considered to be appropriate for health and well-being. The recommendations acknowledge the individual variability by defining the range of hours that 'may be appropriate' for some people. For some adults 6 hours may be enough, and some adults may need 10 hours of sleep.

While general recommendations provide rule-of-thumb amounts agreed upon by experts, it is crucial to consider each individual's unique sleep needs. For example, it's been suggested that athletes need more sleep than the average person.[2] Moreover, an individual's sleep needs can fluctuate from day to day, influenced by factors such as health status, training, and environment.

2.3 Sleep quality

The NSF has provided evidence-based recommendations and guidance regarding indicators of good sleep quality for healthy people at different ages.[9] According to the consensus paper, parameters that reflect sleep continuity (or sleep fragmentation) can be used as measures of sleep quality at most ages. Sleep continuity refers

to a group of those sleep parameters that indicate amount and number of wake bouts during the night. In essence, shorter sleep latencies, fewer awakenings, reduced wake after sleep onset, and higher sleep efficiency all indicate good sleep quality.

In addition to continuity parameters, experts have also evaluated whether the percentages of time spent in different sleep stages could be measures of sleep quality. As a result, studies suggest that deep sleep and REM sleep can serve as indicators of sleep quality in adults. Therefore, a night of reduced deep sleep and elevated REM sleep points to poor sleep quality.

3 Polar Sleep Plus Stages

The Sleep Plus Stages feature developed by Polar automatically measures the amount and quality of sleep and illustrates sleep structure in detail. It consolidates sleep time and the components of sleep quality into one single value: the sleep score. This score compares the previous night's sleep to the science-based indicators of a good night's sleep.

3.1 Benefits

Sleep Plus Stages provides the following benefits:

- Users can see how their sleep proceeded over the course of the night and how much time they spent in each sleep stage and in interruptions.
- Users get a Sleep Score that shows how well they slept compared to the indicators of a good night's sleep based on current sleep science.
- Users get feedback on how well they slept compared to their usual night's sleep.
- With regular sleep tracking, users can learn to identify factors that may affect their sleep.

3.2 Measurement method

Polar's sleep measurement method requires no effort from the user. The only thing they need to do is wear their Polar watch and enable the 'Continuous HR tracking' setting. Sleep Plus Stages automatically recognizes when the user falls asleep and wakes up. To do so, the Sleep Plus Stages algorithm utilizes accelerometry and photoplethysmography measured from the non-dominant wrist. Characteristics of raw 3D acceleration signals reveal hand movements, which is the foundation of Polar's sleep detection. Photoplethysmography is an optical technique that detects pressure pulses traveling through blood vessels. Measuring the times between successive heart beats and analyzing their variation allows classification of sleep into different sleep stages.

3.3 Sleep structure

The total duration between falling asleep and waking up is sleep time. The Polar sleep algorithm classifies each 30-second epoch during this period into light sleep, deep sleep, REM sleep or interruptions (Figure 1). Light sleep corresponds to the two lightest stages of non-REM sleep, while deep sleep corresponds to the deepest stage of the non-REM sleep phase. Sleep interruptions correspond to the bouts when the algorithm detects that the user briefly awakens. Whether the user remembers these interruptions or not depends on their duration. Shorter ones are usually forgotten, while longer ones, lasting 90 seconds or more, are often remembered.

In addition to the parameters shown in Figure 1, Polar's sleep breakdown includes two parameters derived from the interruptions and sleep bouts during the night: actual sleep and sleep continuity. Actual sleep refers to the time the user actually spent asleep, which equals sleep time minus interruptions. It can be presented as both a duration and a percentage of sleep time. Sleep continuity evaluates how continuous sleep was, based on the pattern of interruptions and sleep bouts during the night. The scale is 1-5, where 1 reflects fragmented sleep and 5 indicates very continuous sleep.

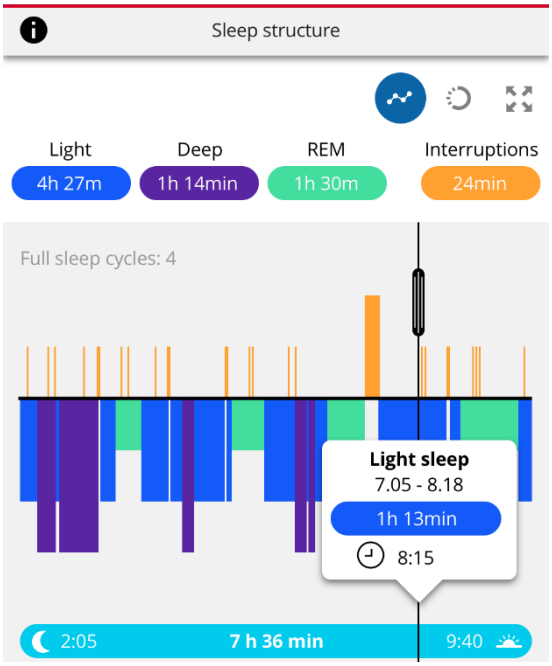

Figure 1. An example of Polar's sleep structure view. Different sleep stages are represented by different colors. Thin and thick yellow bars indicate short and long interruptions in sleep, respectively. This example shows four full sleep cycles. A typical sleep cycle progresses from light sleep to deep sleep, and then back to REM sleep.

3.4 Sleep score

Sleep Plus Stages consolidates the data on the amount and quality of sleep into one single value: sleep score (Figure 2). The six components of the sleep score are grouped into three categories: sleep amount, sleep solidity, and sleep regeneration. Polar research has used the NSF's recommendations and guidance as the foundation for selecting and evaluating the components of the sleep score.[8,9] The sleep score is an average of its components, with a scale of 1–100. The average sleep score for adults is 71.

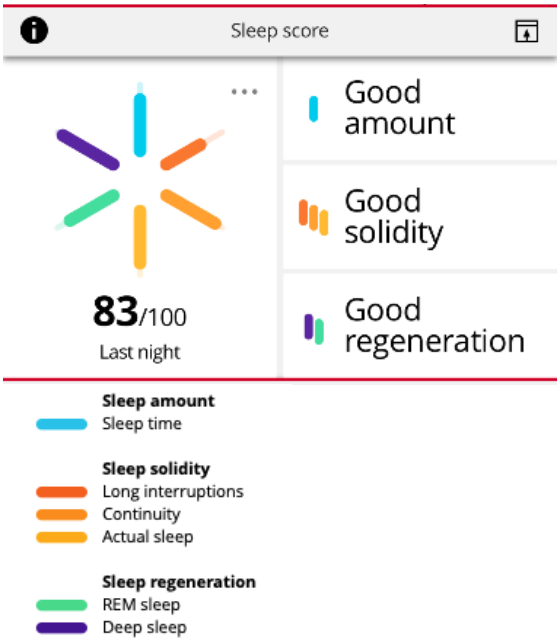

Figure 2. An example of Polar sleep score view. Here, the sleep score value is 83 out of 100. The score consists of six components grouped into three categories: sleep amount, sleep solidity, and sleep regeneration. In this example, each category is evaluated as 'Good'.

Sleep amount evaluates how long the user has slept. Sleep time is compared to the optimal sleep time based on 'Your preferred sleep time' setting and the age-related duration recommendations. Users can set their preferred sleep time, with the default value being eight hours for adults based on the NSF's recommendations. It is important to adjust the setting to match with the user's individual sleep need. Adults get the maximum score from this component when they have slept for at least eight hours and met their preferred sleep time.

Sleep solidity evaluates sleep quality based on the pattern and number of interruptions during sleep. It consists of three components: long interruptions, continuity, and actual sleep.

- A night without any long interruptions yields the maximum score for this component. On average adults have about 16 minutes of long interruptions in sleep.

- The scale for continuity ranges from 1 to 5. A score of five represents sleep without any interruptions and resuts in the maximum score. For adults, the average value is 3.2.
- An actual sleep value close to 100% grants the maximum score. The average actual sleep value for adults is about 93%.

Sleep regeneration gauges sleep quality based on the proportions of restorative sleep stages: REM sleep and deep sleep.

- A REM sleep amount of 25% provides the maximum score for this component of the sleep score. Higher or lower percentages reduce the score. According to the Polar Flow database and multiple scientific studies, the average amount of REM sleep is about 21% of sleep time for adults.[10]
- A deep sleep amount of roughly 17% results in the maximum score. The average amount of deep sleep is about 17% of sleep time for adults, according to the Polar Flow database, which is similar to the percentage reported in scientific literature.[10]

3.5 Textual feedback

With Sleep Plus Stages, in addition to the sleep score, users receive textual feedback on its three categories (sleep amount, sleep solidity, and sleep regeneration). Each of them is evaluated against the characteristics of a good night's sleep, and then graded using a three-step scale: poor, moderate, or good.

Since sleep need and sleep structure are highly individual, each category is also assessed against the user's usual level using a five-step scale: much below usual, below usual, usual, above usual, much above usual. Corresponding visual comparisons are also available for the six individual components of the sleep score. Comparing sleep to one's usual level can help the user to learn how daily choices and lifestyle habits affect sleep.

3.6 Sleep-wake schedule

Users can see their measured sleep-wake schedule from Polar Flow's weekly and monthly sleep graphs. Maintaining a regular schedule is the foundation of a healthy sleep structure, as it helps synchronize the internal sleep regulatory clock with the 24-hour rhythm.The SleepWise™ feature can assist the user in aligning their sleep schedule with their body's internal circadian rhythm. SleepWise™ visualizes the effects of sleep debt and irregular sleep-wake schedule, helping the user make small adjustments to find a better routine. Additionally, a practical way to improve sleep for both athletes and the general population is to follow 'sleep hygiene' recommendations designed to promote healthy sleep (e.g. avoid caffeine, exercise regularly, manage stress, and reduce bedroom noise).[11,12]

3.7 Subjective sleep rating

After getting enough sleep, one should feel alert and energetic to perform well in daily duties and other activities. The Sleep Plus Stages allows users to record their own perception of how well they have slept by rating the previous night's sleep on a five-step scale: very poorly, poorly, okay, well, very well. This may help the user discover the optimal amount and quality of sleep they need. This sleep rating is not considered in the sleep score calculation.

4 Validity

The detection of fell asleep time and woke-up time, as well as classifying the time between these two points into two stages (actual sleep and interruptions), is based on 3D-acceleration data. In the Sleep Plus Stages feature, the four-stage classification of sleep (light, deep, REM, and interruptions) is based on an analysis of the heart's beat-to-beat intervals and 3D-acceleration data.

Independent scientific studies have validated Polar's sleep tracking algorithms and technology against polysomnography—the gold standard for assessing sleep—in healthy adults, children, and adolescents. Polysomnography is based on the simultaneous recording of electroencephalography (i.e. brain activity), electrooculography (i.e. eye

movements), and electromyography (i.e. muscle activity) using scalp surface electrodes. A sleep expert manually scores 30-second epochs of the recording into different sleep stages by following standardized visual identification rules. The main findings of selected validation studies are reported below. Polar sleep parameters and their definitions are provided in Table 1.

Table 1. Definition of sleep parameters, the terms used at Polar, and the terms commonly used in scientific studies.

Definition	Polar	Scientific studies
Timestamp when you fell asleep	Fell asleep time	Sleep onset
Timestamp when you woke up	Woke up time	Sleep offset
Time elapsed between when you fell asleep and when you woke up	Sleep time	Sleep period or sleep interval
Time scored as sleep between when you fell asleep and when you woke up	Actual sleep	Total sleep time or sleep after sleep onset
Time scored as wake between when you fell asleep and when you woke up	Interruptions	Wake after sleep onset

Parent and colleagues[13] examined the validity of Polar sleep tracking in physically active adults (n= 36; 20 women and 16 men, mean ± SD: age 27 ± 4 years, VO_2max 46.8 ± 9.4 mL·kg^{-1}·min^{-1}). The study protocol included measurements with a Polar watch (a prototype of the Polar M600) and polysomnography at home over three separate nights: familiarization night, night without exercise, and night with an exercise session. The exercise session consisted of 6 x 3-minute bouts of treadmill running at an intensity ≥ 80% of the second ventilation threshold, and at ≥80% of the maximum heart rate. Polar's four-stage sleep classification was compared against polysomnography. For the night without exercise, the agreement was (mean ± SD) 60.1 ± 8.1% and a kappa value of 0.39 ± 0.13. For the night with exercise, agreement was 59.2 ± 9.8% and a kappa value was 0.36 ± 0.16. Sleep period time and total sleep time did not differ significantly between Polar sleep tracking and polysomnography. Based on comparisons with previous studies the researchers concluded that Polar sport watch demonstrated equal or better accuracy and agreement with polysomnography in sleep-stage recognition, as compared to other wrist-worn consumer products on the market.

In a study by Miller et al.,[14] six commonly used wearables, including the Polar Vantage V, were compared against polysomnography. Fifty-three adults (26 women, 27 men, mean age ± SD 25.4 ± 5.9 years) wore all six devices simultaneously and slept one night in a sleep laboratory. Epoch-by-epoch comparisons against polysomnography were performed for both 2-stage and 4-stage classifications of sleep. Polar's 2-stage classification showed an agreement of 87% and Cohen's kappa value of 0.44, which indicates a moderate level of agreement. For the Polar 4-stage classification agreement was 51% and a kappa value was 0.28 suggesting a fair level of agreement. Polar Vantage V estimated total sleep time well (mean bias -0.8 minutes, absolute bias 31.2 minutes). These results indicate that the Polar Vantage V is valid for tracking the timing and duration of sleep in real-life settings and can be used as an alternative to polysomnography for 2-stage classification of sleep.

Chinoy and colleagues[15] tested the Polar Vantage V Titan against an electroencephalography (EEG) headband (Dreem 2, Dreem). Although Dreem 2 headband does not provide standard polysomnography, it serves as a feasible reference device for assessing sleep over several nights. Twenty-one adults (12 women, 9 men, mean age ± SD 29.0 ± 5.0 years) slept at home for one week wearing simultaneously four commercial wearables, a research-grade accelerometer (Actiwatch 2, Philips Respironics), and the EEG headband. Epoch-by-epoch comparisons between the Polar watch and the EEG headband showed sensitivity of 0.96, specificity of 0.35, and accuracy of 0.92 for Polar 2-stage classification. In similar comparison between Actiwatch 2 and the EEG

headband, sensitivity was 0.95, specificity was 0.35, and accuracy was 0.90. These results indicate that the Polar sleep tracking method performed against the EEG headband as well as the widely used research-grade accelerometer. Although the researchers also performed 4-stage classification, they did not report overall agreement metrics combining all sleep stages.

Pesonen and Kuula[16] compared Polar fitness watch (a prototype watch of Polar A370) and Actiwatch 2 (Philips Respironics) against polysomnography. Seventeen children (mean age ± SD 11.0 ± 0.8 years) and 17 adolescents (age 17.8 ± 1.8 years) wore both watches alongside an ambulatory polysomnography device, and slept one night at home. Results for Polar's 2-stage classification showed excellent sensitivity (> 0.91), adequate specificity (> 0.77), and excellent accuracy (> 0.90) for both age groups. There was no significant difference in sleep onset, sleep offset, and sleep period time between polysomnography and Polar sleep tracking. On average Polar sleep tracking underestimated actual sleep time by -28.9 minutes in children and by -20.6 minutes in adolescents and overestimated wake after sleep onset by 24.4 minutes in children and by 12.5 minutes in adolescents. These results for Polar watch were comparable or even slightly better than those reported for Actiwatch 2 (see details from reference 16). The researchers concluded that the Polar watch measures sleep at a level generally accepted in clinical and research contexts. Although the Polar prototype watch with the Sleep Plus feature was used in this study, the results apply to the Polar Sleep Plus Stages as well, as both features use the same methodology for detecting sleep and wake.

In conclusion, the above studies provide evidence that Polar sleep tracking performs at a level generally accepted for research use in 2-stage classification of sleep. In a research context, the reported accuracy for 4-stage classification of sleep should be considered. For consumer use, the Sleep Plus Stages feature provides a valid and reliable tool for tracking sustained changes in sleep timing, sleep duration, and time spent in different sleep stages over weeks and months.

5 Limitations

As the measurement is fully automatic, it may detect sleep time inaccurately on some nights. However, users can edit the time they fell asleep and woke up afterwards in the Polar Flow app. If a user is very restless and moves a lot during sleep, Sleep Plus Stages may incorrectly detect that the user is awake when they are actually asleep. It is also possible for Sleep Plus Stages to mistakenly recognize periods of wakefulness as sleep. This can typically happen if the user remains still for long periods but is not actually sleeping.

Sleep Plus Stages estimates sleep stages indirectly based on the heart's beat-to-beat intervals and 3D acceleration data. The Polar photoplethysmography method measures the heart's beat-to-beat intervals accurately at rest and during sleep.[17] However, sometimes, if the watch's wristband is not tight enough, the signal from the optical sensor may be noisy, causing the algorithm to struggle in recognizing sleep stages and resulting in periods of unrecognized states in the Polar hypnogram.

Sleep Plus Stages is developed and validated for use in healthy individuals with normal sleep patterns. It is not designed to detect sleep problems and may not perform accurately in individuals with sleep disorders.

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