WHOOP

THE IMPORTANCE OF SLEEP STAGE TRACKING FOR ATHLETIC PERFORMANCE AND RECOVERY

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Table of Contents

Abstract

The axiom, "practice makes perfect," only tells half the story, we now understand the whole truth: "practice, combined with sleep, makes perfect.[1]"

Sleep's role in athlete performance and recovery is well established; however, the mechanism through which sleep influences these processes remains poorly understood. A key breakthrough in understanding how sleep affects performance came from understanding that sleep is not a singular physiological state, but rather is composed of a set of distinct physiological states with unique processes and purposes.

This paper (1) reviews the role of each of sleep's stages in the physiological performance and recovery of athletes, (2) presents evidence that sleep stage information can more robustly predict next-day athletic performance metrics than can sleep information alone, and (3) concludes that nightly sleep stage monitoring in the athlete population, when applied appropriately, can be used to make training both safer and more effective.

Introduction

Increasing fitness, strength, and athletic performance requires athletes to undergo a significant amount of physical stress[2]. Optimal training requires balancing this stress with appropriate recovery. Recovery hinges on getting an appropriate amount of sleep[3].

Sleep restriction in athletes is associated with significantly increased risk of injury[4], making it perhaps even more important for athletes to reach sleep repletion each night than it is for the general population. In an elite athlete population, with big games, travel and exhaustive demands on their time, making time for sleep is not always an easy task.

In addition to sleep debt posing a greater risk to athletes than to the general population, athletes need more sleep to wake up "debt free", making it that much harder to not carry a sleep debt[5].

> Despite greater need, athletes tend to get less sleep than the general population, at least in part due to factors like demanding training[6,7] and travel[8] schedules that limit available sleep time.

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[1] Walker and Stickgold, 2005
[2] Martin, 1981
[3] Samuels, 2008
[4] Luke et al., 2011
[5] Walters, 2002
[6] Halson, 2014
[7] Sarget et a., 2014
[8] Venter, 2012

Sleep Deprivation and Injuries

The connection between sleep deprivation and increased sports injuries has been demonstrated in numerous studies; the popularity of this topic is not surprising given that each year in the U.S. alone, nearly two million sports injuries require emergency department treatment[9], and another 10 million sports injuries require non-emergent medical care[10], collectively totaling billions in health care costs[11]. However, the consequences of sleep deprivation in athletes are not limited to increased risk of injury; sleep deprivation significantly impairs all aspects of athletic and cognitive performance. One study of collegiate basketball players compared shooting percentage, sprint times, and reaction time before and after changing from their habitual sleep/wake habits to an extended sleep pattern in which they attempted to sleep upwards of 10 hours a day[12]. Not only did the study find performance improvements in every tested metric, but they also saw significant improvements in daytime sleepiness levels, vigor, and fatigue as well as improved self-perception of performance during practice and games, subjectively faster physical recovery times, improved weight training and conditioning, and, as expected, fewer injuries.

Homeostatic Disruption

The connection between sleep-deprivation, increased risk of injury, and diminished performance metrics has been attributed to several inter-related mechanisms including homeostatic imbalance, particularly with regards to the homeostatic processes involved in temperature regulation. As a result, sleep deprivation curbs the body's ability to sweat, preventing adequate cool down and increasing the stress of a workout. In one counterbalanced study, following sleep deprivation, athletes were reported to sweat 27% less than following an adequate night's sleep[13]. This is significant because sweating is how humans maintain body-temperature homeostasis as physical exertion increases. Inability to regulate body temperature therefore leads to overheating, dizziness, cramping, flushing, and weakness – all factors not associated with peak performance.

Additionally, athletes working out following sleep deprivation reported reaching a point of exhaustion 11% faster than their well-rested counterparts[14]. This finding was particularly interesting given that the increase in perceived exertion did not correlate with higher heart rates or metabolic rates, suggesting that the ability to recruit muscle groups to complete exercises (either due to physical limitations or decreased willpower) was diminished.

This is congruent with a 1999 finding that sleep deprivation decreases tolerance to pain[15], which perhaps explains why sleep deprivation decreases the ability to fight through the

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[9] NEISS, 2012
[10] Janda, 2004
[11] NEISS, 2012
[12] Mah et al., 2011
[13] Sawka et al., 1984
[14] Martin et al., 1981
[15] Drewes, 1999

"burn" of exercise and causes athletes to reach their subjective limits faster. This is also consistent with a second study in which one night of sleep deprivation was shown to decrease endurance performance without decreasing cardio-respiratory function. This performance decrease was therefore attributed to differences in perceived exertion[16]. Anaerobic power metrics appear to be unaffected by a single night of acute sleep deprivation, however, after extended sleep deprivation, signs of impairment emerged[17].

The Stages of Sleep

Healthy adult humans spend about one-third of their lives asleep[18]. Despite the prevalence of this behavior, the scientific community has yet to reach a consensus as to exactly what purpose sleep serves[19]. In 1976, researchers defined sleep as a period of ceased bodily functioning[20], and it was not until 2001 that one researcher concluded that sleep is physiologically different from other states of relative inactivity such as unconsciousness, coma, and hibernation[21].

Sleep is composed of at least two stages, **REM** (rapid eye movement) and **non-REM**; in medical and academic literature, non-REM Sleep is further divided into 2 or 4 stages, as illustrated in **Figure 1**.

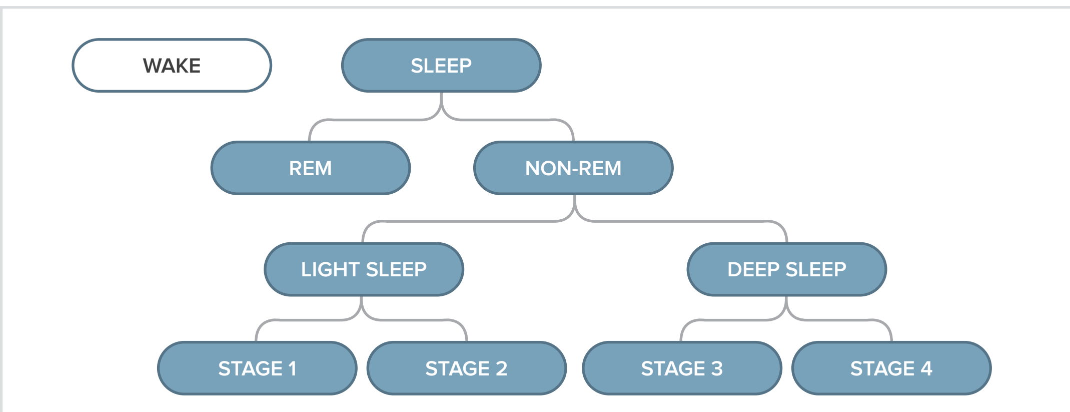

Figure 1, Diagram of the breakdown of sleep into stages with various tiers of granularity. At the highest tier, a distinction is made only between sleep and wake. Below that, sleep is divided into REM and non-REM. In the third tier, non-REM is divided into Light and Deep Sleep. In the final tier, Light Sleep is divided into Stages 1 and 2, and Deep Sleep into Stages 3 and 4.

For the remainder of this discussion, we will focus on the third tier of granularity, in which sleep has four stages: **(1) Wake**, **(2) REM**, **(3) Light**, and **(4) Deep**.

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[16] Oliver et al., 2009
[17] Souissi et al., 2003
[18] Lee, 1997
[19] Madje and Krueger, 2005
[20] Watson, 1976: 1042
[21] Stores, 2001

NOTE: Deep Sleep is commonly referred to as Slow Wave Sleep for the slow, synchronized EEG waves observed during this phase[22].

Analysis

While technically the absence of sleep, we include Wake among the stages of sleep because it is prevalent throughout the night in both extended and brief periods. These brief periods, often called arousals, are important because they are individually negligible, and therefore not remembered the next morning; however, most people experience nearly 20 per night, which in total can account for over an hour of lost sleep. Figure 2 shows the distribution of sleep disturbances in WHOOP athletes between January 1, 2015 and December 31, 2015.

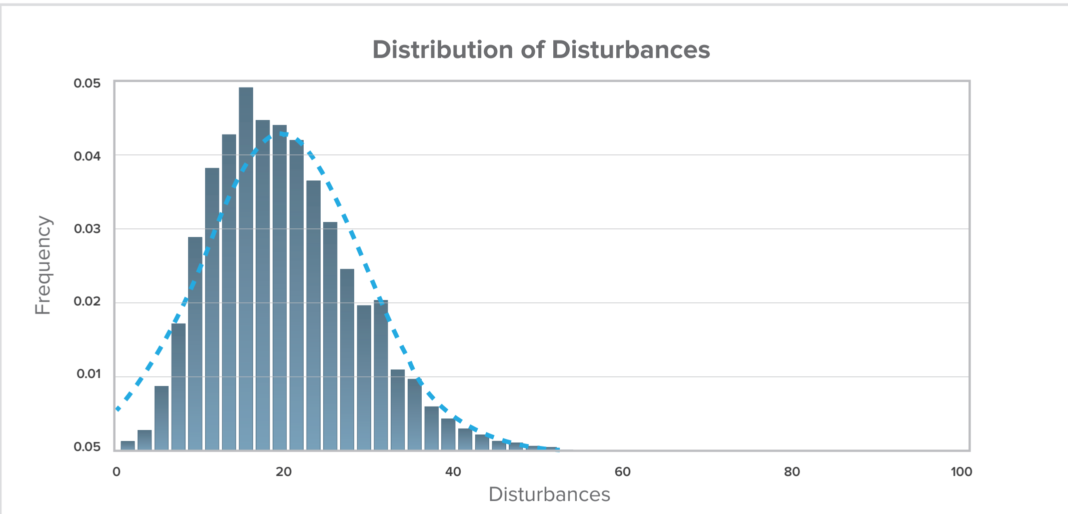

Figure 2, Distribution of disturbances per user per night. Sampled from all sleeps of at least 4 hours recorded on the WHOOP platform between January 1, 2015 and December 31, 2015. A dashed trend line plotted in blue shows the average number of arousals is 19.3, with a standard deviation of 9.4.

"About Eight Hours"

The results presented in Figure 2 are more significant in light of a 2007 study of 2,113 subjects that asked subjects to self-report total sleep time, and found that subjects overestimate total sleep by 61 minutes (95% CI: 57-65 minutes)[23]. This study's findings are consistent with other literature showing that humans are poor assessors of lost sleep and total sleep time[24], suggesting that maintaining a sleep journal that relied on self-reporting would not result in similar benefits to rigorous arousal tracking.

[22] Rechtschaffen and Kales, 1968
[23] Silva et al., 2007
[24] Mah et al., 2011

Within sleep, each stage serves a distinct purpose. REM Sleep's primary functions relate to mental restoration, including memory consolidation[25] and the stabilization of spatial and procedural memory[26]. REM is therefore critical after learning complex techniques or strategies[27] and after acquiring new motor skills[28]. Whereas REM Sleep serves to restore the brain, Deep Sleep serves to restore the body. During Deep Sleep, growth hormone, the hormone responsible for muscle repair and growth, is produced in high quantities[29]. By one estimate, 95% of the daily production of growth hormone occurs during Deep Sleep[30]. Perhaps unsurprisingly, there is a quantitative relationship between the total amount of time spent in Deep Sleep and the amount of growth hormone secreted during the night[31].

Sleep Duration and Efficiency

Within the analyzed WHOOP athlete population, the average amount of time dedicated to sleep, that is time spent both sleeping and attempting to sleep, is 8.0 hours with a standard deviation of 1.3 hours. Figure 3 illustrates this distribution.

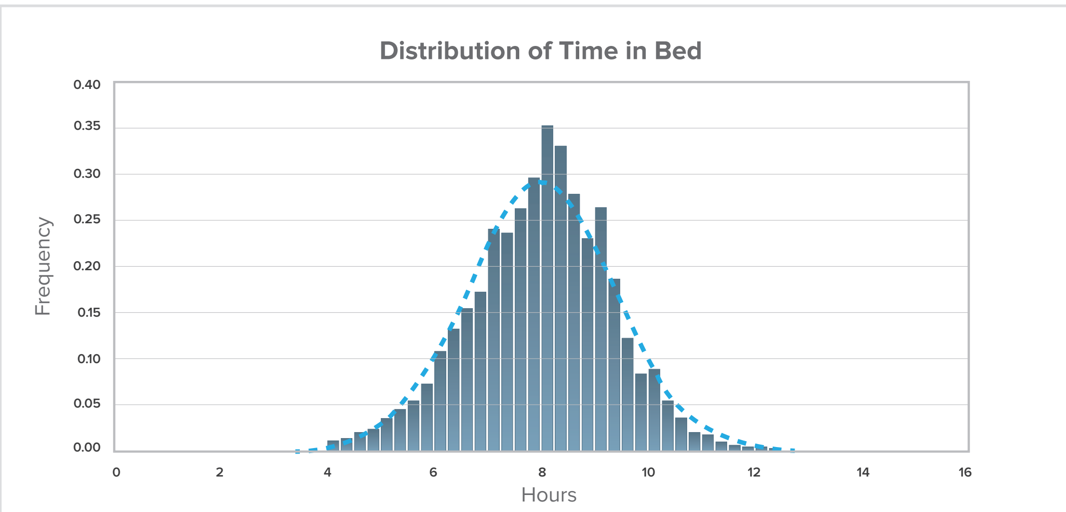

Figure 3, Distribution of time dedicated to sleep per 24-hour period in WHOOP athletes between January 1, 2015 and December 31, 2015.

Expectedly, not all time spent trying to sleep is spent actually asleep. The average WHOOP

[25] Davenne, 2009
[26] Siegel, 2001
[27] Meire-Koll et al., 1999
[28] Buchegger et al., 1991
[29] Walters, 2002
[30] Gunning, 2001
[31] Van Cauter et al., 1997

athlete between January 1, 2015 and December 31, 2015 got 6.9 hours of sleep, with a standard deviation of 1.3 hours. Figure 4 shows the distribution of actual sleep time in WHOOP athletes.

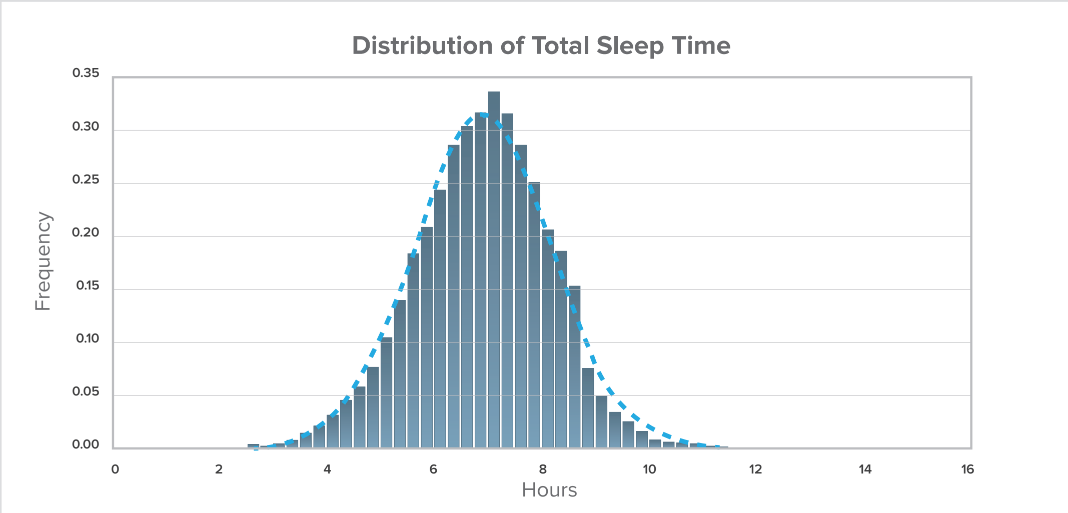

Figure 4, Distribution of time spent asleep per 24-hour period in WHOOP athletes between January 1, 2015 and December 31, 2015.

The information presented in Figures 3 and 4 together show that the average WHOOP athlete gets about 51 minutes of sleep per hour spent trying to sleep. Figure 5 shows the distribution of sleep efficiency (time spent asleep per unit time spent attempting sleep) across WHOOP athletes.

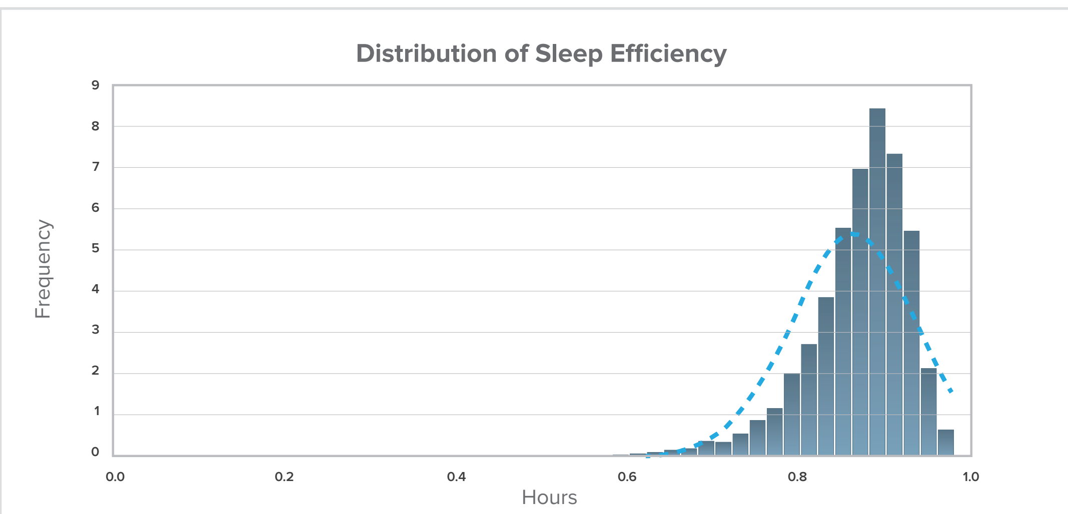

Figure 5, Distribution of sleep efficiency in WHOOP athletes between January 1, 2015 and December 31, 2015. Average efficiency is 86.4%, standard deviation: 7.2%.

Sleep Stages: A Good Indicator of Sleep Deprivation

A typical night of sleep in a healthy, non-sleep deprived adult begins with Light Sleep and then transitions into Deep Sleep within 15 minutes. Within 40 to 90 minutes, the first REM episode will occur. This is typically the shortest REM episode, and rarely lasts longer than 10 minutes. The typical person will experience 3 to 4 additional REM periods that increase in duration as the night progresses[32]. As REM periods lengthen, Deep Sleep periods shorten and may even cease. Figure 6 shows a real example of sleep recorded using a WHOOP physiological monitor.

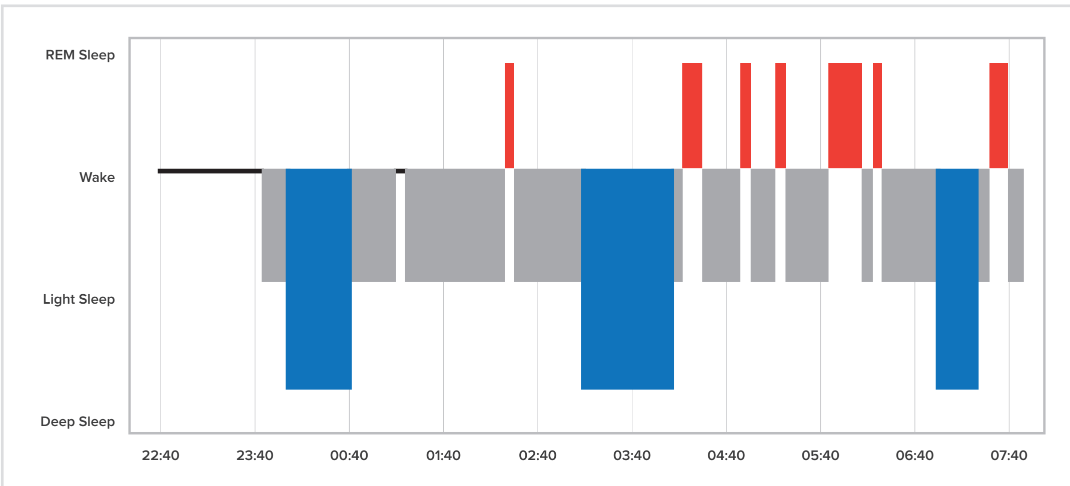

Figure 6, Graph of the change of sleep stage over time for a real WHOOP user. The x-axis values show time in the user's local time zone, y-axis values show the sleep stage. For clarity, each sleep stage is also color-coded: Light Sleep is indicated by a gray bar, Deep Sleep is indicated by a blue bar, and REM Sleep is indicated by an orange bar. Black lines mark the two periods of Wake. Note: sleep stages are displayed with 4-minute resolution.

Notice how the sleep illustrated in Figure 6 begins with a Wake period, enters sleep with a brief Light Sleep episode, and then transitions into an extended period of Deep Sleep. As expected, REM periods become longer and more frequent as the night progresses, while at the same time Deep Sleep becomes less frequent.

Table 1 shows the average distribution of the four stages of sleep in a complete night of normal sleep.

[32] Stiller and Postolache, 2005

Stage	Percentage of Sleep
Light Sleep	47 - 60%
Deep Sleep	13 - 23%
REM Sleep	20 - 25%
(not including Sleep Latency)	< 5%

Table 1, Distribution of sleep stages during a typical night of sleep in a healthy adult[33].

We note that because the distribution of sleep stages changes as the night progresses, the information presented in Table 1 breaks down when sleep is restricted. In situations of acute sleep deprivation, REM is recovered only after Deep Sleep has recuperated, causing REM to appear unusually late in the night (example shown in Figure 7); however, in situations of chronic sleep deprivation, REM occurs prematurely, and can even occur before the first Deep Sleep Episode[34] (example shown in Figure 8).

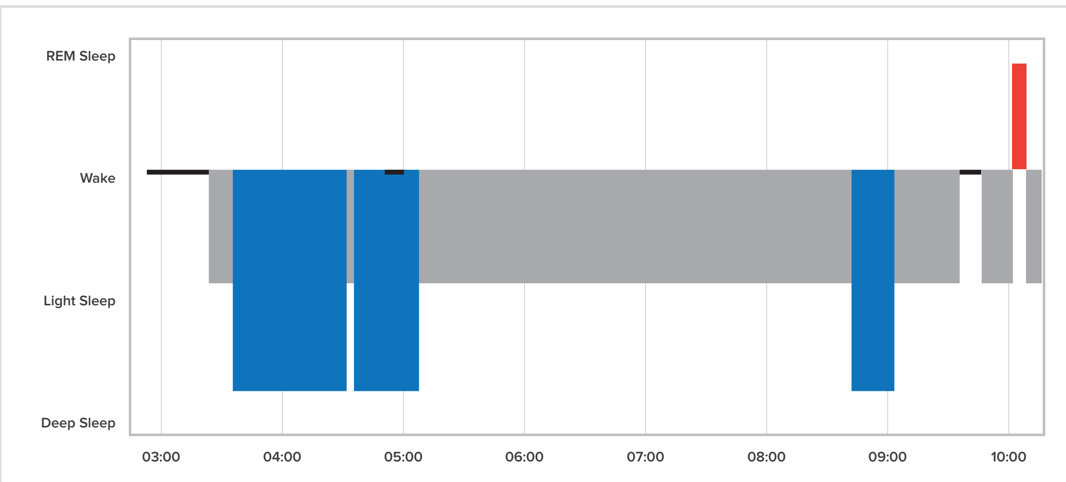

Figure 7, Graph of the change of sleep stage over time for a real, acutely sleep deprived WHOOP user. X-axis values show time in the user's local time zone, y-axis values show the sleep stage. As in Figure 3, each sleep stage is also color-coded: Light Sleep is indicated by a gray bar, Deep Sleep is indicated by a blue bar, and REM Sleep is indicated by an orange bar. Black lines mark periods of Wake. Note: sleep stages are displayed with 4-minute resolution.

[33] Carskadon and Dement, 2011
[34] Carskadon and Dement, 1989

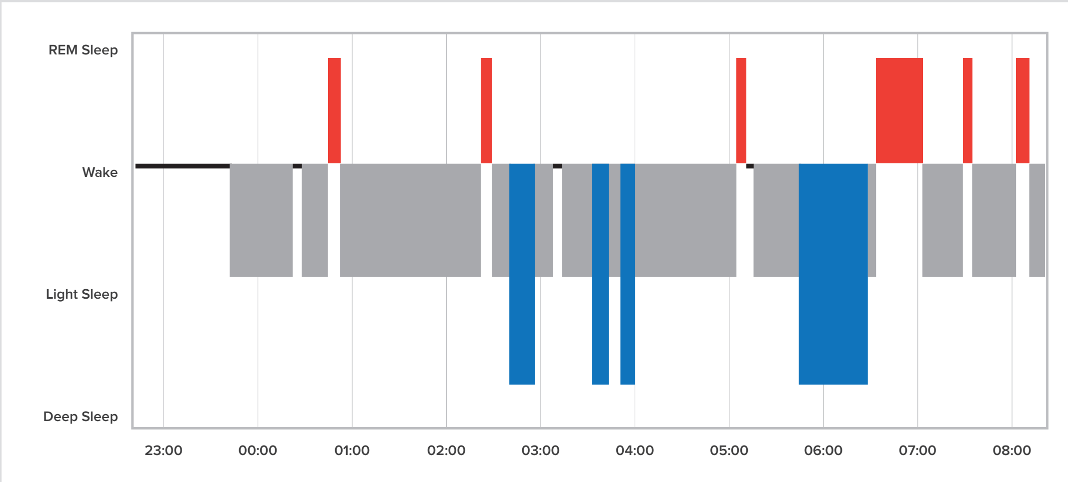

Figure 8, Graph of the change of sleep stage over time for a real, chronically sleep deprived WHOOP user. X-axis values show time in the user's local time zone, y-axis values show the sleep stage. As in **Figure 6**, each sleep stage is also color-coded: Light Sleep is indicated by a gray bar, Deep Sleep is indicated by a blue bar, and REM Sleep is indicated by an orange bar. Black lines mark periods of Wake. Note: sleep stages are displayed with 4-minute resolution.

Changing Patterns

Tracking changes in sleep stage distribution and patterns over time can provide valuable insight into an individual's current state of sleep deprivation in a way that accounts for inter-individual differences in actual sleep need. This is important because the accepted wisdom that adults need 8 hours of sleep per 24-hour day[35] problematically oversimplifies the variability of true human experience. In reality, an individual's sleep need, or the amount of sleep their body requires to become sleep replete on a given night, varies dramatically among individuals and within individuals across nights. Factors that affect inter-individual variability include genetics[36], biological sex, health, fitness level, and age[37], while factors that affect intra-individual variability include activity level[38], recent sleep deprivation, and acute changes in health.

After accounting for all these factors, healthy adult sleep need ranges from 7 to 10 hours. This means that an individual could be getting the "recommended 8 hours" and still be severely sleep deprived.

This is significant because a well-kept sleep diary would not reveal a problem in an athlete who regularly gets 8 or even 9 of the 10 hours of sleep he needs. However, with proper sleep stage monitoring, specifically monitoring REM and Deep Sleep patterns, signs of chronic sleep deprivation can be revealed. This could be extremely important for this athlete, because

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[35] Loehr and Schwartz, 2005
[36] Karacan and Moore, 1979
[37] Tonetti et al., 2008
[38] Bompa and Haff, 2009

in addition to being associated with greater risk of all cause mortality, **chronic sleep deprivation has been correlated with a 68% greater risk of sport-related injury over the course of a 21-month period when compared to athletes with similar training loads getting a sufficient amount of nightly sleep[39].**

Recovery = Performance

Together, the information presented in Figures 3-5 illustrate that Wake accounts for a significant and highly variable portion of the time dedicated to sleep. Figures 6-8 build on this by showing that the time spent in sleep's most restorative phases (Deep and REM) is also highly variable. In order to thoroughly illustrate the significance of this variability, and therefore the value of rigorous sleep stage monitoring, we next examined the relationships between time in bed and time in various stages with various next-day athletic performance and recovery metrics.

HRV

Heart rate variability (HRV) is a measure of the variability in the time interval between heartbeats. Morning HRV readings positively correlate with the cardiovascular and nervous systems' acute adaptability to training[40], making it a well studied and widely utilized metric for predicting and understanding health and performance in athletes[41]. Because inter- and intra-individual variability in average HRV is high, studying trends in HRV over time provides greater predictive power than does analyzing individual readings in isolation[42].

Across all professional and NCAA athletes using the WHOOP system in the 3 month period between 10-20-2015 and 1-20-2016, the coefficient of correlation (r^2) between time dedicated to sleep and HRV was 43% smaller than the r^2 value between HRV and Deep Sleep and 47% smaller than the r^2 value between HRV and combined time spent in sleep's most restorative phases (Deep Sleep and REM Sleep). Total time in bed's lower r^2 value means that it is a poorer predictor of HRV, and therefore – according to decades of published research – of exercise performance.

In order to confirm that monitoring nighttime sleep stages allows for a better prediction of same-day athletic performance than would simply monitoring time in bed, we examined our collegiate athletes' self reported exercise performance during the same 3 month period. In gathering this data, WHOOP never intervened regarding the intensity or types of athletic activities our athletes performed, but after each workout, we provided a survey through it's mobile application in which athletes had the opportunity to rate their performance on a discrete 5-point scale.

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[39] Milewski et al., 2014
[40] Karim et al., 2011
[41] Plews et al., 2013
[42] Plews et al., 2012

Algorithmically determined total sleep time (ie: excluding any within-sleep wake periods) correlated with self-reported same day athletic performance 1.6 times better than did the athletes' reported times in bed.

Summary

There is a unique impact of each sleep stage on next-day athletic performance and recovery. Significant evidence exists demonstrating that athletes are both not getting enough sleep and are not getting as much sleep as they think. A sleep journal or similar mechanism of sleep reporting that relies on self-reporting is flawed. To understand the impact on recovery, sports scientists need to embrace sleep stage tracking. Coaches and trainers supporting athletes can use objective data to educate and encourage this practice. It is WHOOP's belief, that the next frontier in athlete evolution will be fueled by better sleep.

References

Bompa TO, Haff GG (2009) Periodization: Theory and Methodology of Training (5th ed.) Champaign, IL: Human Kinetics.

Bonnect M, Arand D (1995). Should We Be Taking More Sleep? Sleep, 18: 908-911.

Buchegger J, Fritsch R, Meier-Koll A, Riehle H (1991) Do Trampolining and Anaerobic Physical Fitness Affect Sleep? Perceptual and Motor Skills, 73: 243:252.

Carskadon MA, Dement WC (1989) Normal Human Sleep. In Kryger et al., Principles and Practice of Sleep Medicine (3-13) Philadelphia, PA: WB Saunders.

Carskadon MA, Dement WC (2011) Normal Human Sleep - An Overview. Principles and practice of sleep medicine, 5th edition, (pp 16-26). St. Louis: Elsevier Saunders.

Davenne D (2009) Sleep of Athletes: Problems and Possible Solutions. Biological Rhythm Research, 40: 45-52.

Drewes AM (1999) Pain and Sleep Disturbances with Special Reference to Fibromyalgia and Rheumatoid Arthritis. Rheumatology 38: 1035-1038.

Gunning L (2001) Enhancing Recovery: Impact of Sleep on Performance. Sports Coach (23): 33.

Halson S (2014) Sleep in Elite Athletes and Nutritional Interventions to Enhance Sleep. Sports Med. 44:S13-23.

Janda D (2004) The Awakening of a Surgeon: A Family Guide to Preventing Sports Injuries and Death, The Institute for Preventative Sports Medicine, p. 208.

Karacan I, Moore CA: Genetics and Human Sleep. Psychiatr Ann 1979; 9:11-23.

Karim N, Hasan JA, Ali SS (2011) Heart Rate Variability – A Review. Journal of Basic and Applied Sciences 7:71-77.

Lee KA (1997) An Overview of Sleep and Common Sleep Problems. ANNA Journal 26:614-6:25.

Loehr J, Schwartz T (2005) The Power of Full engagement. New York, NY: Free Press.

Luke A, Lasaro RM, Bergeron MF, Keyser L, Benjamin H, Brenner J, d'Hemecort P, Grady M, Philpott J, Angela S (2011) Sports-Related Injuries in Youth Athletics: Is Overscheduling a Risk Factor? Clinical Journal of Sport Medicine, 21:308-314.

Madje JA, Krueger JM (2005) Links Between the Innate Immune System and Sleep. Journal of Allergy and Clinical Immunology, 116: 1188-1198.

Mah CD, Mah KE, Kezirian EJ, Dement WC (2011) The Effects of Sleep Extension on the Athletic Performance of Collegiate Basketball Players. Sleep 34: 943-950.

Martin BJ (1981) Effect of Sleep Deprivation on Tolerance of Prolonged Exercise. European Journal of Applied Physiology and Occupational Physiology, 47:345-354

Meier-Koll A, Bussman B, Schmidt C, Neuschwander D (1999). Walking Through A Maze Alters the Architecture of Sleep. Perceptual and Motor Skills, 88: 1141-1159.

Milewski M, Skaggs D, Bishop G, Pace J, Ibrahim D, Wren T, Barzdukas A (2014) Chronic Lack of Sleep is Associated with Increased Sports Injuries in Adolescent Athletes. J Pediatric Orthop 34: 129-33.

NEISS Data Highlights – 2012. Consumer Product Safety Commission (CSPC), Bethesda, MD, quoted in: Misra A (2014) Common Sports Injuries: Incidence and Average Charges. ASPE Issue Brief, Department of Health and Human Services.

Oliver SJ, Costa RJS, Laing SJ, Bilzon JLJ, Walsh NP (2009) One Night of Sleep Deprivation Decreases Treadmill Endurance Performance. European Journal of Applied Physiology. 107:155-161.

Plews, D. J., Laursen, P. B., Kilding, A. E., & Buchheit, M. (2012). Heart Rate Variability in Elite Triathletes, Is Variation in Variability the Key to Effective Training? A Case Comparison. European Journal of Applied Physiology, 112: 3729-3741.

Plews DJ, Laursen PB, Stanley J, Kilding AE, Buchheit M (2013) Training Adaptation and Heart Rate Variability in Elite Endurance Athletes: Opening the Door to Effective Monitoring. Sports Med. 1-9.

Rechtschaffen A, Kales A (1968) A Manual of Standardized Terminology, Techniques and Scoring System of Sleep Stages in Human Subjects. Brain Information Service/Brain Research Institute, University of California.

Samuels C (2008) Sleep, Recovery, and Performance: The New Frontier in High-Performance Athletics. Neurol Clin. 26:169-180.

Sargent C, Halson S, Roach GD (2014) Sleep or Swim? Early-Morning Training Severely Restrics the Amount of Sleep Obtained by Elite Swimmers. European Journal of Sport Science 14:S310-S315.

Sawka MN, Gonzalez RR, Pandolf KB (1984) Effects of Sleep Deprivation on Thermoregulation During Exercise. Am J Physiol Regul Intgr Comp Physiol 246:R72-R77.

Siegel JM (2001) The REM Sleep-Memory Consolidation Hypothesis. Science 294: 1058-1063.

Silva GE, Goodwin JL, Sherrill DL, Arnold JL, Bootzin RR, Smith T, Walsleben JA, Baldwin CM, Quan SF (2007) Relationship Between Reported and Measured Sleep Times: The Sleep Heart Health Study (SHHS). Journal of Clinical Sleep Medicine 3:622-630.

Souissi N, Sesboue B, Gauthier A, Larue J, Davenne D (2003) Effects of One Night's Sleep Deprivation on Anaerobic Performance the Following Day. European Journal of Applied Physiology. 89:359-366.

Stiller JW, Postolache TT (2005) Sleep-Wake and Other Biological Rhythms: Functional Neuroanatomy. Clinics in Sports Medicine 24: 205-235.

Stores G (2001) A Clinical Guide to Sleep Disorders in Children and Adolescents. Cambridge, UK: Cambridge University Press.

Tonetti L, Fabbri M, Natale V (2008) Sex Difference in Sleep-Time Preference and Sleep Need: A Cross-Sectional Survey Among Italian Pre-Adolescents, Adolescents, and Adults. Chronobiology International. 25:745-759.

Van Cauter E, Plat L, Scharf MB, Leproult R, Cespedes R, L'Hermite-Baleriaux M (1997) Simultaneous Stimulation of Slow-Wave Sleep and Growth Hormone Secretion by Gamma-Hydroxybutyrate in Normal Young Men. Journal of Clinical Investigation, 100: 745-753.

Venter RE (2012) Role of Sleep in Performance and Recovery of Athletes: A Review Article. South African Journal for Research in Sport, Physical Education and Recreation 34:167-184.

Walker MP, Stickgold R (2005) It's Practice, with Sleep, That Makes Perfect: Implications of Sleep-Dependent Learning and Plasticity for Skill Performance. Clinics in Sports Medicine, 24: 310-317.

Walters PH (2002) Sleep, the Athlete, and Performance. National Strength and Conditioning Association 24: 17-24.