The Impact of Sleep Duration on Performance Among Competitive Athletes: A Systematic Literature Review

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The Impact of Sleep Duration on Performance Among Competitive Athletes: A Systematic Literature Review

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Abstract: The athletic advantage of sleep, although commonly touted by coaches, trainers, and sports physicians, is still unclear and likely varies by sport, athletic performance metric, and length of sufficient or insufficient sleep. Although recent literature reviews have highlighted circadian and nutritional factors that influence different aspects of athletic performance, a systematic summary of the effects of sleep duration and sleep quality on performance among competitive athletes is lacking. Here we systematically review the relationship between sleep duration and sleep quality and objective athletic performance among competitive athletes across 19 studies representing 12 sports. Taken holistically, we find that the sports requiring speed, tactical strategy, and technical skill are most sensitive to sleep duration manipulations. Furthermore, longer-term sleep manipulations are more likely than acute sleep manipulations (whether deprivation or extension) to affect athletic performance. Thus, the importance of sleep for competitive athletes to achieve high performance is dependent on the demands of the sport as well as the length of sleep interventions. In light of the limited number of studies investigating sleep quality and performance, the potential relevance of subjective sleep quality remains an interesting question for future work.

Key Words: athletic performance, aerobic, anaerobic, strength, tactical, technical, sleep quality, sleep duration

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INTRODUCTION

High-quality, sufficient sleep is often presumed to be necessary for multiple factors contributing to sports performance, such as promoting physical and mental recovery from rigorous training regimens, minimizing the risk of injury, and preventing in-game fatigue and lapses in concentration. Indeed, coaches, trainers, and physicians all emphasize the importance of good sleep hygiene for athletes, especially in the days and nights leading up to competition.[1–4] Significant efforts have been underway to better understand and characterize rest and functional recovery among athletes,[5–7] with the implicit goal of helping athletes optimize their performance. Outside of the sports science community, 2 separate sleep time duration consensus panels have recently advised that young adults and adults[8,9] get at least 7 hours of sleep per night. However, specific guidelines for competitive athletes do not exist. The definition of adequate high-quality sleep and the validity of the long-held precept that sleep is essential for peak athletic performance have not been systematically verified via review of the relevant literature.

Several recent literature reviews have assessed the science on sleep and athletic performance. One of these reviews investigated the effects of circadian disruptions, sleep disturbance, and diurnal variation in sports performance. This review article confirmed that circadian disruptions and sleep disturbance alter sports performance, but results were mixed based on specific skill sets tested and methodologies employed.[10] Another focused on the physiological interplay between physical performance, exercise, and sleep.[11] Yet another highlighted nutritional interventions that could be used to improve sleep among athletes to maximize performance.[12] The physiological, emotional, and cognitive ramifications of reduced sleep in athletes can also be considerable, especially when sleep deprivation is prolonged.[13]

In general, these studies indicate that sleep extension tends to improve athletic performance, whereas total sleep deprivation (24-hour) and partial sleep deprivation (less than one night) tend to impair performance, although anaerobic or explosive muscle power performance seems less sensitive to sleep deprivation than does aerobic or endurance performance.[10] With respect to diurnal variations in performance, peak performance is often observed in the evening across various sports, and the effects of circadian misalignment on performance are exacerbated when traveling eastward, thereby temporally shifting one's environment forward.[10] Regular exercise, particularly in the evening and nighttime, has been shown to improve sleep quality among healthy non-athlete adults, challenging the conventional idea that exercise in the evening is detrimental to optimal sleep hygiene.[11] On the other hand, exercise can cause increased nocturnal heart rate

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variability and maintain sympathetic autonomic tone that normally dampens at night.[14] Many professional athletes not only exhibit low total sleep duration (<7 hours/night), but also report lower sleep quality (eg, increased nighttime awakenings, lower sleep efficiency), especially after night matches, and even after home games.[15–19] The effects of increased exercise and especially night exercise on functional recovery and subsequent performance among athletes remain unclear, however.

From a physiological perspective, sleep has been shown to aid in restoration of immune function and muscle and cartilage repair following strenuous exercise and physical stress/strain. For example, as exercise regimens increase in volume and vigor, the risk of upper respiratory tract infections increases, an effect that is exacerbated by sleep deprivation.[20–22] Mechanistically, natural killer cell activity, which aids the host's response to viral pathogens, decreases with loss of total sleep time and decreased sleep efficiency, whereas cytokines such as interleukin-6 (IL-6; involved in mounting a lymphocytic response to pathogens) are depressed in subjects experiencing at least partial sleep deprivation.[23–25] This may help explain the enhanced susceptibility to infection in the setting of sleep deprivation. Likewise, sleep deprivation has been shown to dysregulate normal circadian fluctuations in the catabolic hormone cortisol and the anabolic hormones growth hormone, and testosterone, which may lead to delays in repair of articular cartilage and muscle, thus impairing functional recovery.[11,26] Furthermore, sleep deprivation impedes replenishment of muscle glycogen stores following exercise, compromising the energy supply for both repair of myofibrillar micro-damage and subsequent contractile use.[27,28]

Sleep deprivation can also impair glucose metabolism, increasing one's risk of developing obesity and type II diabetes mellitus, whereas caloric restriction or diets high in fat can disrupt sleep architecture.[12] Meanwhile, diets rich in tryptophan, large neutral amino acids, and the nucleotides uridine monophosphate and adenosine monophosphate improve various sleep indices and also promote muscle repair and recovery as well as immune function following exercise.[12,29–32]

Importantly, however, none of the aforementioned studies focused specifically on sleep duration as a predictor of athletic outcomes among competition-level athletes. Given the high level of training and exercise endured by athletes engaged in relatively high-stakes events (compared to the average recreational player), the consequences of sleep duration and quality on their practice and performance are particularly important. Furthermore, specific effects on sports requiring varying skills, such as those incorporating tactics and decision-making, highly technical skills, strength, or endurance, have not been well parsed. Finally, rigorous experimental studies have contributed to key insights into the question of whether and how sleep and performance interact in high-level competitive athletes.[15,33–40] With the professional sports industry in North America valued in the multi-billion dollar range,[41] the question of how sleep duration impacts sports performance carries considerable financial, apart from academic, as well as scientific interest. The present work is novel in that it systematically reviews the relationship between sleep quantity/quality among competition-level athletes and objective performance outcomes. Further, we identify differences in methodologies and measurement, including an assessment of the various types of athletic outcomes considered (eg, aerobic, tactical, technical, and strength).

METHODS

We conducted a systematic literature search in PubMed for original scientific research publications related to sleep duration and objective performance outcomes among competitive athletes. The following terms were used for searches conducted between July and August 2016, with follow-up searches during February 2017: "sleep AND (athletes OR athletics) AND performance," "sleep deprivation AND athletes," "sleep AND performance AND elite (athletes OR athletics)," "sleep AND elite athletics," "sleep AND professional (athletes OR athletics)," "sleep extension AND (athlete OR athletics) AND performance," and "sleep extension AND athletes." These searches returned 907 articles.

We then reviewed all of the abstracts and used the following inclusion criteria to refine our article selection: At least one sleep quantity or quality metric and at least one objective performance metric must have been included. Studies must have been conducted with competitive (professional, elite, or competition-level, but not recreational) athlete participants of all ages. Sleep duration must have been measured the night before the performance outcome. We included studies of both team and individual sports. We used the following exclusion criteria: Studies should not have been conducted with nonathletes (eg, military, firefighters, healthy sedentary or recreationally active volunteers), or those with injury or pathology present (eg, concussion and heat-related illness), or under nonphysiological or extreme environmental conditions (eg, alcohol consumption, fasting, and high altitude). We further excluded studies in which the only performance metric used was self-reported self-evaluation of performance. We excluded studies not written in English or translated into English. We included both experimental and observational studies with or without control conditions. Finally, we consulted an expert in the field (R.D.) to review the list of included studies and suggest others relevant to the current review. See Figure 1 for a flow diagram of the articles included.

In total, we identified 20 studies that conformed to inclusion and exclusion criteria. After this screen, one study was further excluded because the outcome depended on 2 player performance. Among the remaining 19 studies, 15 were experimental and 4 were observational. Sports included soccer, basketball, tennis, marathon and ultra-marathon running, cycling, swimming, triathlon, rugby, weightlifting, judo, taekwondo, karate, and gymnastics.

RESULTS

Table 1 describes all studies that met our inclusion criteria. Of note, objective performance outcomes varied among the studies, ranging from sport-specific performance to general athletic performance. Athletic performance outcomes that have been independently validated and shown to be reliable indicators of the intended metric are indicated with an asterisk.[42–48]

For sports that included in their performance assessments at least one predominantly aerobic or one predominantly anaerobic outcome (eg, endurance exercise or muscle

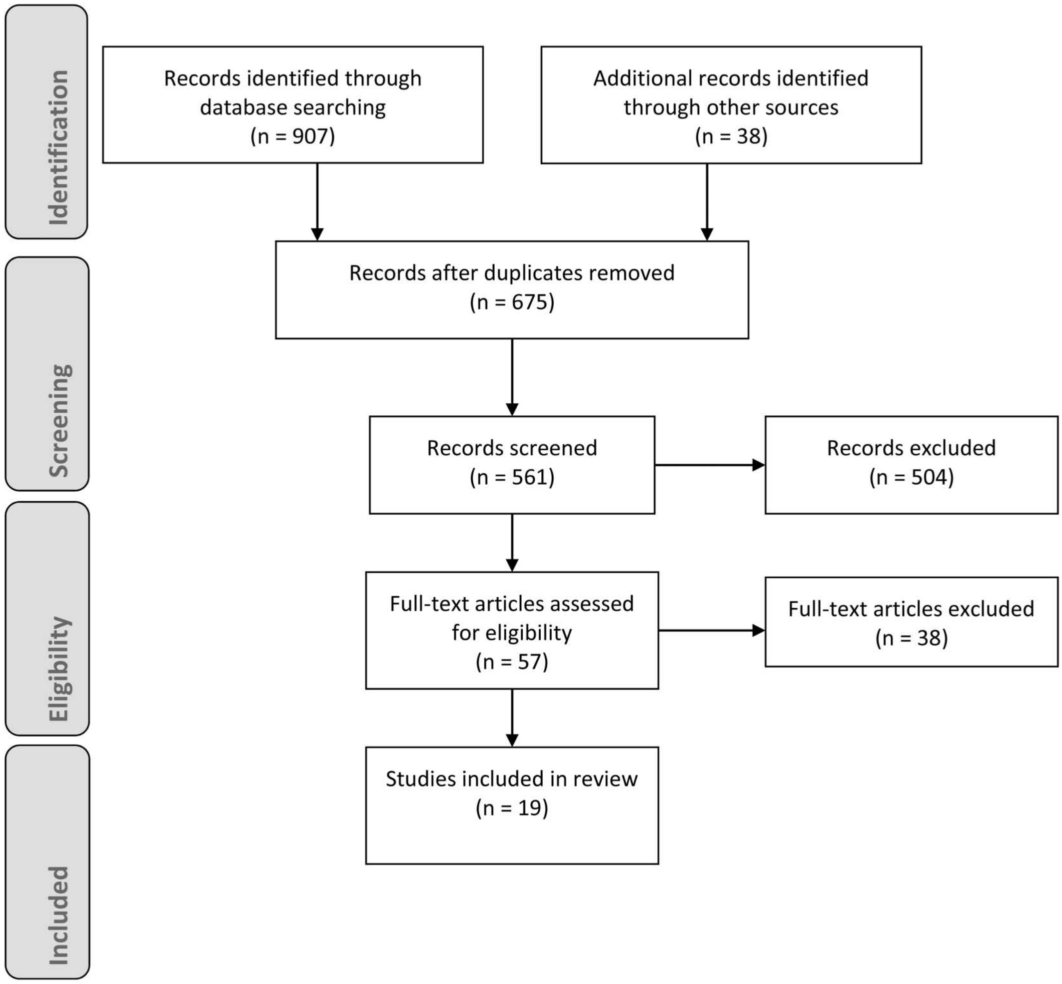

Figure 1. Flow diagram of literature review.

strength/power, respectively), we classified the results of the studies as either positive (+), negative (−), or null (0) in Table 2. We defined positive results as those in which sleep was positively associated with performance (ie, greater sleep quantity and improved performance, or vice versa), negative results as those showing the inverse association, and null results showing no association. To provide more precise information beyond the valence of the association, we also included the specific effect and magnitude of the effect for studies that found statistically significant effects and provided such information (Table 2). Among 13 such studies, we found that 9 reported positive associations,[22,34–36,38,40,49–52] 0 reported negative associations, and 4 reported null results.[15,17,33,53] Out of the 8 studies that measured purely anaerobic outcomes, 6 were positive and 2 were null. Out of the 3 studies that measured purely aerobic outcomes, 2 were positive and 1 was null. Of those that measured composites scores incorporating both aerobic and anaerobic components, 1 was positive and 1 was null. We further categorized these studies by whether they included a strength-based outcome, eg, weightlifting capacity (Table 2). Of the 3 studies, 2 were positive for these strength-based outcomes and 1 was null. Of the 6 studies that included speed-based outcomes, 5 were positive for these speed-based outcomes, whereas 1 was null. Among those that included both strength-based and speed-based outcomes, 2 were positive and 2 were null.

We next compared studies in which a tactical or technical/motor coordination-based outcome was measured (Table 3). We defined tactical outcomes as those requiring strategy, teamwork, or decision-making, and we defined technical/motor coordination-based outcomes as those requiring fine motor skills, such as tennis serving or basketball shooting, or physical coordination such as passing balls or performing gymnastic movements. Out of 6 such studies, 1 included at least one tactical outcome[54] and all 6 included at least one technical/motor coordination-based outcome.[34,35,37–39,54] We again classified these studies as positive, negative, or null and included the specific effect and magnitude where applicable, as described above. Strikingly, we found that all 6 studies reported positive associations between sleep duration and performance (Table 3).

Finally, we grouped experimental studies according to whether the sleep interventions were acute (defined as less than or equal to 48 hours) or longer term (defined as greater than or equal to 1 week), which also varied in terms of whether they involved sleep deprivation or extension. We

TABLE 1. Characteristics of Included Studies

Study	Sport	Study Design	Sample Size	Measure of Sleep Duration	Measure of Sleep Quality	Objective Performance Outcome(s)
*Ben Cheikh[52tbl1fnlowast]	Karate	Experimental, within-subjects design	12 karate athletes	24 h TSD	N/A	Maximal isometric force production of biceps brachii muscle
*Blumert[33]	Weightlifting	RCT	9 national competitive weightlifters	Sleep diary—recall of duration	Sleep diary	Snatch, clean and jerk, front squat weight lifted (kg)
				Baseline night (mean 8 hours sleep) vs 24 h TSD		
*Cook[36]	Rugby	RCT	16 professional rugby players	Sleep diary for total sleep duration (2 conditions—8 h or <6 h)	REST-Q	Bench press, squat, bent row. Measured voluntarily chosen workload = # repetitions * load (kg)
Cook[34]	Rugby	RCT	10 professional rugby players	Sleep diary; subjects instructed to sleep either 7-9 h or 3-5 h	N/A	Rugby passing skill test
Duffield[38]	Tennis	Experimental, within subjects	8 highly trained tennis players	Sleep diary for minutes in bed, 24 h TSD,	N/A	Total, forehand, and backhand stroke counts, forced and unforced errors, time in match play, stroke rate per min and player load, sum of triaxial accelerometry
*Fullagar[15]	Soccer	RCT	20 semi-professional soccer players	Actigraphy to measure night sleep and naps (means TD: 8:44 sleep + 0:57 nap, DM: 8:20 sleep + 0:30 nap, NM: 5:43 sleep + 1:17 nap)	Sleep restfulness (scale from 1 to 5)	Jump height, force production, Yo-Yo intermittent recovery test, submaximal intermittent running test
Hausswirth[22]	Triathlon	Experimental	40 trained triathletes	Wrist actigraphy to measure sleep duration (functionally overreached: 7:09 at baseline; 6:36 3rd wk overload)	Perceived sleep quality, sleep efficiency, and fragmentation index	Workload on cycle ergometer (watts)
Lastella[17]	Distance running	Observational	103 marathon runners	Survey-reported amount of sleep precompetition night (average: 6:38 sleep)	Sleep quality from −3 to +3 relative to a "usual night"	Relative performance, defined as difference between expected and actual performance time expressed as a percentage
Léger[54]	Sailing	Observational	8 elite sailing racers	Polysomnography or electro-oculography to measure sleep night before each leg of race (total sleep time 93.2 min in leg 1 and 155 min in leg 2)	PSQI, Spiegel Sleep Index, Epworth Sleepiness Scale, polysomnography or electro-oculography to measure REM vs non-REM before each leg of race	Ranking in race
*Mah[35]	Basketball	Experimental, within subjects	11 varsity basketball players	2-4 wk baseline (mean 7.8 h/night) followed by 5-7 week extension (mean 10.4 h/night)	N/A	Free throw shooting accuracy, timed sprint, and reaction time test
*Mah[49]	Swimming	Experimental, within subjects	5 varsity swimmers	Actigraphy, sleep diary. 2 wk baseline "usual sleep" followed by extension to 10 h/night for 6-7 wk.	Epworth Sleepiness Scale	15 m sprint, reaction time, turn time, and kick strokes
*Mejri[40]	Taekwondo	Experimental, within subjects	10 national taekwondo competitors	Reference night—participants slept ~7 h. PSD: 3 or 4 hours of SD.	N/A	Yo-Yo intermittent recovery test

TABLE 1. Characteristics of Included Studies *(Continued)*

Study	Sport	Study Design	Sample Size	Measure of Sleep Duration	Measure of Sleep Quality	Objective Performance Outcome(s)
*Mougin[53]	Unspecified highly trained athletes	Experimental	8 highly trained athletes	Self-reported delayed bedtime until 3 AM	N/A	30 s Wingate test
*Reyner[37]	Tennis	RCT	16 varsity level tennis players	Actigraphy, reference night 6.67 hours sleep vs 2-2.5 h PSD	N/A	Serving accuracy
*Schwartz[39]	Tennis	Experimental, within subjects	12 varsity tennis players	Sleep diary—recorded hours per night; after baseline and then asked to extend sleep by 2 h/night for 1 wk.	N/A	Serving accuracy
Silva[56]	Gymnastics	Observational	67 elite gymnasts	Subjective recall of duration (highest scoring: 8:30, 8:32 and lowest scoring: 7:41, 8:27 on weekdays and weekends, respectively	ESS; PSQI	Performance rank in competition
*Skein[69]	Rugby	RCT	11 amateur rugby league players	Global positioning system (GPS) device worn as cervical harness. 8 hours sleep (control) vs 24 h TSD	N/A	Countermovement jump (CMJ) distance, knee-extensor maximal voluntary contraction (MVC), and voluntary activation (VA)
*Souissi[50]	Judo	Experimental, within-subjects	12 competitive judokas	Laboratory-monitored baseline (7:30 sleep) vs 4 h sleep deprivation (slept in laboratory)	N/A	Handgrip strength, maximal voluntary contraction, and Wingate test
Staunton[55]	Basketball	Prospective cohort design	17 elite basketball players	Triaxial accelerometers to measure total sleep duration (TST: 8.2 h double-header; 7.1 h baseline; 7.3 h match day)	N/A	Basketball efficiency statistic = (Points + Rebounds + assists + steals + blocks) − (missed field goals + missed free throws + turnovers)

**SD = sleep deprivation.*
DM, day matches; NM, night matches; PSD, partial sleep deprivation; PSQI, Pittsburgh Sleep Quality Index; RCT, randomized controlled trial; REST-Q, Recovery-Stress Questionnaire; TD, training days; TSD, total sleep deprivation.

found that 7/10 acute sleep manipulation studies yielded positive results, whereas 4/4 longer-term sleep manipulation studies yielded positive results (Table 4). We further sub-classified these experimental studies as either sleep extension (defined as enhancing sleep quantity) or sleep deprivation (defined as diminishing sleep quantity). Among the 10 acute intervention studies, 2 involved sleep extension, while 8 involved sleep deprivation. One acute sleep extension study was positive, whereas the other was null, and 6/8 deprivation studies were positive. Among the 4 chronic sleep intervention studies, 2 involved extension and 2 involved deprivation, and all 4 found positive effects of sleep duration on performance.

We were finally curious to determine whether subjective sleep quality would be associated with performance. Among the 20 included studies, 7 recorded measures of sleep quality, ranging from validated sleep quality scales to sleep diary entries.[15,17,22,33,36,49,55] Of these studies, 3 observed positive associations between sleep quality and performance,[22,49,55] 2 observed no association,[15,17] whereas the rest did not attempt to use the measure of sleep quality to predict performance.

DISCUSSION

This literature review, although diverse in the range of sports, methods, and outcomes studied, provides several stylized facts that can inform sleep research and competitive athletes. First, out of all the published studies we reviewed, none found a negative association between sleep duration and any performance outcome. All of the results reviewed showed that either the increased sleep duration has a positive effect on athletic performance or the results were neutral. Note that among studies reporting significant positive results, effect sizes varied considerably (Tables 2-4), likely due to differences in the duration of sleep deprivation/extension experienced as well as differences in outcome measures.

Second, when considering the aerobic and anaerobic characteristics of sports, it seems that aerobic activity is more sensitive to sleep duration compared to anaerobic activity, including strength testing. For instance, Mejri et al[40] found that depriving competitive taekwondo boxers of a mere 3 to 4 hours of sleep significantly impaired performance on the Yo-Yo intermittent recovery test. By contrast, Blumert et al[33] employed a relatively severe sleep

TABLE 2. Summary of Studies Measuring Anaerobic versus Aerobic Outcomes

Author	Sport	Aerobic or Anaerobic Outcome?	Strength- or Speed-Based Outcome?	Valence of Finding (+, −, 0)	Effect and Magnitude*
Ben Cheikh[52]	Karate	Anaerobic	Strength	+	More sleep → 15% longer time engaging biceps brachii in maximum force
Blumert[33]	Weightlifting	Anaerobic	Strength	0	N/A
Cook[36]	Rugby	Anaerobic	Strength	+	More sleep → increased total workload (effect size: 2.33)
Duffield[38]	Tennis	Both	Speed	+	More sleep → increased time in play and stroke rate (effect sizes: >0.9)
Fullagar[15]	Soccer	Both	Both	0	N/A
Hausswirth[22]	Triathlon	Anaerobic	Both	+	More sleep → increased power on ergometer (+10 W)
Lastella[17]	Distance running	Aerobic	Speed	0	N/A
Poussel[51]	Distance running	Aerobic	Speed	+	Data not presented
Mah[35]	Basketball	Anaerobic	Speed	+	More sleep → 9% increase in free throw accuracy, 9.2% increase in 3-point field goal percentage
Mah[49]	Swimming	Aerobic	Speed	+	More sleep → 7% faster sprint; 17% faster reaction time; 9% faster turn time
Mejri[40]	Taekwondo	Anaerobic	Speed	+	More sleep → approximately 25% increase in Yo-Yo intermittent recovery test distance†
Mougin[53]	Unspecified	Anaerobic	Both	0	N/A
Souissi[50]	Judo	Anaerobic	Both	+	More sleep → 3.1-8.4 kg increased handgrip strength; 15%-24% increased maximum voluntary contraction; 3.9%-9.0% increased peak power on Wingate; 2.6%-6.6% increased mean power on Wingate

** Due to different sleep deprivation/extension study designs and outcome measures, magnitudes across studies are not comparable. Refer to individual studies for more details.*
† Precise data were not available. Results in Figure 1A.

deprivation protocol by depriving 9 national-caliber collegiate weightlifters of 24 hours of sleep and yet failed to identify adverse effects on any of the various weightlifting exercises examined. Relatedly, for both endurance and explosive, power-based exercises, it has been well documented that sleep deprivation is associated with increased perceived effort.[56–58] Still, the relationship between perceived effort and objective performance has not been widely validated and is a topic for future investigation.

Third, of the studies that measured outcomes requiring either tactical and/or technical skills, most find benefits of sleep on performance. Tennis serving accuracy and basketball shooting were both improved by long-term sleep extension interventions,[35,39] and tennis serving accuracy suffered when players were deprived of 2 to 2.5 hours of sleep at the beginning of the preceding night.[37] Regarding studies conducted in players of team sports that incorporated tactics and decision-based outcomes to a broader extent, soccer as well as rugby players exhibited performance deficits after nights of decreased sleep duration.[34] These results are in line with other literature demonstrating clear neurocognitive deficits in the setting of inadequate sleep in the general population, reviewed thoroughly elsewhere.[59,60]

Finally, when looking at the methodologies of the experimental studies, we found that the studies that altered sleep duration on a longer-term timescale were more likely to show an effect than those that altered sleep duration acutely. Interestingly although most acute sleep interventions involved sleep deprivation and yielded positive results, there were inconsistent results among the 2 acute sleep extension studies.[15,38] Conversely, the majority of longer-term sleep intervention studies involved sleep extension and showed positive results.[35,39,49] Taken together, these findings suggest that on a short timescale, sleep deprivation may be more harmful than sleep extension is beneficial to performance, although in the longer term, sleep extension may contribute to improved performance. On the other hand, more research is warranted regarding potential adverse effects of chronic sleep loss on athletic performance.

The reliability and precision of the various measurements may present challenges in interpretation of these studies. For example, "maximal" voluntary muscle contraction and voluntarily chosen training load are variable across subjects.[61,62] On the other hand, "running economy," the oxygen cost associated with a given running velocity, has low variability among highly trained runners and is significantly

TABLE 3. Summary of Studies Measuring Tactical or Technical Outcomes

Study	Sport	Tactical Outcome?	Technical/Motor Coordination-Based Outcome?	Finding (+, −, 0)	Effect and Magnitude*
Cook[34]	Rugby	None	Yes	+	More sleep → increased mean passing accuracy of approximately 20% on dominant and non-dominant sides†
Duffield[38]	Tennis	None	Yes	+	More sleep → increased time in play and stroke rate (effect size: >0.9)
Mah[35]	Basketball	None	Yes	+	More sleep → 9% increase in free throw accuracy, 9.2% increase in 3-point field goal percentage
Reyner[37]	Tennis	None	Yes	+	More sleep → approximately 20%-30% increase in serving accuracy‡
Schwartz[39]	Tennis	None	Yes	+	More sleep → increased serving accuracy out of 50 (deuce and add side together): after sleep extension: 17% improvement vs before sleep extension
Staunton[55]	Basketball	Yes	Yes	+	More sleep → improved basketball efficiency statistic (r = 0.39 — 0.22 range)

** Due to different sleep deprivation/extension study designs and outcome measures, magnitudes across studies are not comparable. Refer to individual studies for more details.*
† Precise data were not available. Results in Figure 1.
‡ Precise data were not available. Results in Figure 1B.

correlated with cardiorespiratory parameters used to assess aerobic capacity.[63] A meta-analysis of the reliability of various measures of muscle power previously identified that field running tests tended to be more reliable than treadmill running tests, tests lasting up to 1 minute tended to be more reliable than those lasting greater than 1 minute (likely due to increased variability in muscle movement and limb positioning), and isokinetic tests tended to be more reliable when measuring muscle extension versus flexion.[62] Somewhat reassuringly in the context of the present review, this meta-analysis also found that measurements taken from athletes were more reliable than those taken from non-athlete subjects.

With respect to the validity of outcome measures reported as performance indicators, the nature of the sport (eg, team vs individual) may be an important determinant of whether what is measured in the laboratory translates to the actual game. For instance, for team-based sports requiring complex game structure such as soccer, measures of muscle force production or running speed are likely insufficient to provide an accurate assessment of in-game performance, although they may be helpful in making gross approximations and predictions.[64] Of course, actual performance metrics from real or simulated games would be the ideal outcomes to quantify for such sports in future investigations. More specifically, for performance outcomes included in the current review, the following have been independently validated and shown to be reliable measures of athletic performance: Yo-Yo intermittent recovery (YYIR) test, isometric muscle contraction, squat, countermovement jump, free sthrow basketball shooting, tennis serving, shuttle-running tests, and Wingate test.[42–48] In Table 1, we have indicated studies employing previously validated and reliable metrics of objective performance with asterisks (as per the criteria discussed above). Still, more work will be required to further validate the various performance outcomes measured in the studies reviewed in the present work, especially those involving complex, team-based measures such as composite game performance scores and passing accuracy. Likewise, given the high inter-individual variability of sleep variables used across the included studies, these metrics will also require further investigation to determine their precision and reliability as predictors of athletic performance.

Importantly, we chose to require at least one objective performance measure among our inclusion criteria. The previous work relying on self-perceived performance, although informative in understanding the potential effect of sleep loss or gain on sports psychology,[15] may not accurately reflect actual performance, as was the goal of the present work. However, under certain circumstances, self-perceived pre-game wellness (including self-reported sleep quality) may be predictive of objective in-game performance.[65] More research will be needed to assess the validity of player-reported performance and objective performance, especially when athletes exhibit compromised sleep.

Several experimental studies are particularly illustrative of the various trends in the results we have just outlined. To address the question of whether one night of sleep extension would be sufficient to improve various fitness indices among semi-professional soccer players, Fullagar et al[15] tested a sleep hygiene intervention. The investigators implemented a sleep hygiene strategy (SHS) designed to maximize sleep duration and limit stimulation before bedtime to test whether this would be sufficient to improve either anaerobic (jumping height and force production) or aerobic endurance (Yo–Yo intermittent recovery level 2, YYIR2) performance after late-night soccer matches. Implementing a randomized design, they assigned 20 participants to follow either their normal post-match sleep routine [non-SHS (NSHS)] or a SHS involving early dimming of lights and lights out by midnight, cool room temperature, and no technology or light stimulation for 15 to 30 minutes before bedtime. Actigraphy was used to measure sleep patterns, and sleep diary was used for subjective recall of sleep quality. Despite finding that those assigned to the SHS indeed exhibited increased sleep duration after the night match relative to those in the NSHS group, the investigators failed to identify any improvements in

TABLE 4. Summary of Experimental Study Findings

Author	Sport	Acute or Longer-Term Sleep Intervention?	Sleep Extension or Deprivation?	Finding (+, −, 0)	Effect and Magnitude*
Ben Cheikh[52]	Karate	Acute	Deprivation	+	More sleep → 15% longer time engaging biceps brachii in maximum force
Blumert[33]	Weightlifting	Acute	Deprivation	0	N/A
Cook[36]	Rugby	Acute	Deprivation	+	More sleep → increased total workload (effect size: 2.33)
Cook[34]	Rugby	Acute	Deprivation	+	More sleep → increased mean passing accuracy of approximately 20% on dominant and non-dominant sides†
Duffield[38]	Tennis	Acute	Extension	+	Increased time in play and stroke rate in intervention vs control (effect size: >0.9)
Fullagar[15]	Soccer	Acute	Extension	0	N/A
Hausswirth[22]	Triathlon	Longer term	Deprivation	+	Decreased power on ergometer (−10 W vs control)
Mah[35]	Basketball	Longer term	Extension	+	9% increase in free throw accuracy, 9.2% increase in 3-point field goal percentage in sleep extension group vs control
Mah[49]	Swimming	Longer term	Extension	+	Faster sprint (sleep extension group: 93% vs control); faster reaction time (sleep extension group: 83% vs control); faster turn time (sleep extension group: 91% vs control)
Mejri[40]	Taekwondo	Acute	Deprivation	+	More sleep → approximately 25% increase in Yo-Yo intermittent recovery test distance‡
Mougin[53]	Unspecified	Acute	Deprivation	0	N/A
Schwartz[39]	Tennis	Longer term	Extension	+	Increased serving accuracy out of 50 (deuce and add side together): after sleep extension: 117% improvement vs before sleep extension
Skein[69]	Rugby	Acute	Deprivation	+	Slower sprint time with sleep deprivation (sleep deprivation day 2: 2.78 sec vs control day 2: 2.74 sec)
Reyner[37]	Tennis	Acute	Deprivation	+	More sleep → approximately 20%-30% increase in serving accuracy§

Due to different sleep deprivation/extension study designs and outcome measures, magnitudes across studies are not comparable. Refer to individual studies for more details.
† Precise data were not available. Results in Figure 1 of Cook[34].
‡ Precise data were not available. Results in Figure 1A of Mejri[40].
§ Precise data were not available. Results in Figure 1B of Reyner[37].

countermovement jump height, countermovement jump force production, or YYIR2 performance, tested over the following 2 days.

On the other hand, as we have discussed, studies of acute sleep deprivation, especially those measuring technical performance outcomes, tended to yield positive results. Given that sleep is often disrupted the night before athletic competition,[66] athletes involved in sports requiring these types of skills are likely to be particularly sensitive to sleep manipulations and thus should be counseled regarding the importance of sleep for game performance. Relatedly, chronic sleep extension studies have demonstrated significant benefits to athletes.[35,49] Thus, strategies to improve sleep not only the night before an important sports event but also in the weeks leading up to this event are likely to be fruitful in improving performance.

In this review, we have summarized and synthesized recent findings in the realm of sports and sleep science. One of the challenges of conducting such a literature review is that the study methodologies vary a great deal, as do the individual sports, making comparisons of effects and magnitudes of effect sizes across studies difficult. Additionally, unlike many studies of athletic performance and sleep conducted in non-athletes and recreational sports players, studies incorporating high-level competitors are limited, especially those implementing experimental approaches. Even among the best-controlled studies, sample sizes are small and sleep measurements vary considerably, with some studies measuring sleep duration objectively through polysomnography or actigraphy and others relying on self-report. All of these factors limit the scope of the conclusions that can be drawn. Nevertheless, they do provide valuable information about when sleep does or particularly when sleep does *not* seem to play a key role in influencing performance. Future research may seek to use larger sample sizes and standardize tests of athletic performance in order to identify optimal sleep standards, in addition to standardizing sleep metrics and incorporating more objective sleep data. In particular, here we focused on studies investigating sleep duration, although sleep timing is likely to be a relevant factor as well. As sleep onset and wake time have previously been shown to influence performance and recovery,[5] future studies should aim to incorporate this information.

Given these suggestions for improving future research, there are many opportunities for innovative research on this topic. One area in particular may be about how generalizable these findings are to other sports. Given the wide range of methodologies and used in these studies, another research goal would be to harmonize measures across studies and conduct a meta-analysis. Another area to investigate is trade-offs between wake time activities (eg, athletic practice) and sleep. For example, is it beneficial for swimmers to practice early in the morning even at the expense of their sleep? Research also should seek to investigate the mechanisms by which aerobic, tactical, and technical performance attributes may be preferentially sensitive to changes in sleep patterns.

One limitation of the present work is that although the number of hours and/or nights of sleep interventions across studies varied, sleep duration was only measured the night before performance assessment. Thus, in order to obtain a more complete picture of sleep quantity and quality, future research should aim to measure sleep across the entire study period. Another limitation is that few of the studies examined explicitly the relationship between subjective sleep quality and performance, especially using validated sleep quality questionnaires such as the PSQI and ESS. Thus, this remains an open question that will be important to be investigated in the future. Once all these data are gathered, feasible and effective interventions should be developed, implemented, and evaluated to improve the sleep health and optimal performance of athletes.

In conclusion, the importance of sleep for professional athletes to achieve high performance varies by the cognitive and physical demands of the sport. However, because most sports require integration of aerobic fitness, tactical skills, and technical skills, competitive athletes will likely benefit from an increase in sleep duration.

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