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REVIEW

Effects of Acute Sleep Deprivation on Sporting Performance in Athletes: A Comprehensive Systematic Review and Meta-Analysis

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Objective: Using meta-analysis to comprehensively and quantitatively evaluate the impact of acute sleep deprivation on different sports performance of athletes, this study aims to provide scientific guidance for coaches in optimizing and adjusting training and competition arrangements.

Methods: Establishing literature inclusion and exclusion criteria, we conducted searches in both Chinese and English databases. Using stata 14.0, we analyzed 75 indicators from 27 included literature, focusing on three aspects: the impact of acute sleep deprivation on overall athletic performance, the impact on sporting performance across various athletic abilities, and the disparities in athletic performance between morning and afternoon following acute sleep deprivation.

Results: The effect size of acute sleep deprivation on overall athletic performance was −0.56 ($P<0.05$). Sub-analyses revealed effect sizes of −0.23 ($P<0.05$) for whole night sleep deprivation, −1.17 ($P<0.05$) for partial sleep deprivation at the end of the night, and −0.25 ($P>0.05$) for partial sleep deprivation in the beginning of the night. The effect sizes of acute sleep deprivation on high intensity intermittent exercise, skill control, speed, aerobic endurance, and explosive power indicators were −1.57, −1.06, −0.67, −0.54, and −0.39 respectively ($P<0.05$). The effect sizes of acute sleep deprivation on the overall athletic performance in the morning and afternoon were −0.30, and −1.11, respectively ($P<0.05$).

Conclusion: Acute sleep deprivation significantly impairs the overall athletic performance of athletes, with a more pronounced negative impact observed with partial sleep deprivation at the end of the night. Various types of exercise performance are adversely affected by acute sleep deprivation, with magnitude of impact ranking high intensity intermittent, skill control, speed, aerobic endurance, and explosive power. Following acute sleep deprivation, athletes' overall sporting performance in the afternoon is inferior to that in the morning.

Keywords: acute sleep deprivation, athletes, athletic ability, sporting performance, meta-analysis

Introduction

Sleep is a crucial physiological activity with profound implications for various aspects of health. Adequate sleep significantly contributes to enhanced cognitive function, mood regulation, immunity system function and metabolic process.[1] In the realm of competitive sports, the experiences of world-class high-level athletes underscore the significance of quality sleep as a non-specific training factors influencing sporting performance. This realization has sparked extensive research and discourse with the competitive sports community.[2,3] High-quality sleep not only fosters optimal concentration and mental states during competitions, leading to heightened competitive levels, but also facilitates post-high-intensity training and competition recovery. This, in turn, reduces the risk of injuries and extends athletes' sporting careers[4].

In comparison to the general population, athletes often grapple with sleep deprivation due to factors such as morning and late evening training sessions, inter-state or international travel cross different time zones, unfamiliar sleeping

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environments, and pre-competition anxiety.[5] Furthermore, studies examining global sleep quality reveal that 50% to 78% of elite athletes experience sleep disturbances, with approximately 22% to 26% enduring highly disrupted sleep.[4] This underscores the significance and urgency of investigating the impact of acute sleep deprivation on athletes' performance across various competitive levels. In this regard, exploring the sleep patterns of athletes at different proficiency levels warrants further investigation to provide a more comprehensive perspective and guidance. Long-term sleep deprivation or sleep disorders can significantly compromise subsequent sporting performance, diminishing overall sporting levels and athletic achievements. Notably, chronical sleep deprivation is less common among athletes, with acute sleep deprivation triggered by factors like event pressure, injuries, or temporary adjustments, being more prevalent, particularly before major competitions. Acute sleep deprivation refers to a state in which an individual remains partially or fully awake for a brief period (usually 24–72 hours).[6] It is categorized as full night sleep deprivation (lasting over 24 hours without sleep) and partial sleep deprivation (involving partial sleep within a 24-hour period). The latter includes late sleep deprivation (falling asleep later than usual, eg, starting sleep at 3 a.m.) and early-rising sleep deprivation (waking up earlier than the normal waking time, eg, getting up at 3 a.m.).

Until now, existing findings regarding the effects of acute sleep deprivation on different sports and performances vary. Some studies contend that acute sleep deprivation has no significant negative impact on athletes' anaerobic endurance,[7,8] maximum strength,[9,10] aerobic endurance,[11] etc., while others report contrasting conclusions.[12,13] Most related studies qualitatively explore the negative impact of acute sleep deprivation without comprehensive quantitative analysis.[14–16]

To our knowledge, limited research has delved into the impact of acute sleep deprivation on athletes' sporting performance. To address this gap, we conducted a meta-analysis, applying the principles of evidence-based medicine. This systematic review aims to answer three critical questions: 1) does acute sleep deprivation negatively impact athletes' sporting performance, and to what extent? 2) What specific negative effects does acute sleep deprivation have on athletes' sporting performance, and are there variations in these effects? 3) How does athletes' sporting performance differ in the morning and afternoon following acute sleep deprivation?

Research Methods

Literature Search Strategy

We conducted this systematic review and meta-analysis in accordance with the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) guidelines. The study protocol was registered with the International Prospective Register of Systematic Reviews (PROSPERO) (registration number: CRD42024517744). The completed PRISMA checklist is provided as Supplementary File 1. Searches encompassed seven databases, including both English and Chinese electronic databases (PubMed, Web of science, ProQuest, Scopus, CNKI, WANFANG and VIP), up until May 13, 2023. Three sets of search terms related to athlete, sleep and performance were separated by "OR" and combined "AND" using the Boolean operator. The search term combinations were as follows: (athlete* OR "elite athletes" OR "competitive athlete" OR player OR sportswoman OR sportsman) AND (sleep OR "sleep deprivation" OR "sleep restriction" OR "sleep loss" OR "sleep quality" OR "sleep duration" OR "Insufficient sleep") AND (performance OR competition OR "technical skills" OR tactical OR strength OR anaerobic OR aerobic OR accuracy OR coordination OR flexibility OR balance OR speed).

Following the preliminary search, 177 Chinese documents were obtained (Chinese documents were limited to articles included in CSSCI, CSCD, and Chinese Core Journals Overview), along with 1336 English documents.

Literature Inclusion and Exclusion Criteria

This study established comprehensive inclusion criteria across five dimensions: research subjects, intervention measures, control/comparison measures, outcome indicators and research design. Specifically: 1) Research Subjects. Inclusion of athletes, defined as professionals engaged in sports. Subdivision of athletes into two levels: high-level athletes and ordinary athletes, based on the descriptions provided in the included literature; 2) Experimental research. Acceptance of subjects who underwent at least one acute sleep deprivation protocol, such as overnight sleep deprivation (SD), partial sleep deprivation at the beginning of the night (PSDB), and partial sleep deprivation at the end of the night (PSDE); 3) sporting Performance Exercise. Reporting of at least one of the following exercises related to sporting performance: aerobic endurance, anaerobic endurance, explosive power, maximum strength, speed, sports skills (such as serving accuracy), etc.; 4) Data Completeness. Requirement for complete data sets before and after the intervention experiment.

Exclusion criteria for literature: 1) Non-Chinese and English literature, abstracts, dissertations, conference papers, etc.; 2) The method of sleep deprivation is non-acute sleep deprivation, specifically those where the sleep deprivation duration for athletes extends for 1 week or more; 3) The data before and after the experimental intervention are incomplete.

Literature Screening and Data Extraction

The titles of the search literature were imported into the Note Express reference management software. After removing duplicates, two authors (MS and LJJ) independently screened the titles, abstracts, and full-text versions of the retrieved studies. Any disagreements were resolved through consensus with a third author (MJG). Subsequently, data extraction was carried out by two independent reviewers (MS and LJJ) using the designated data extraction table. Finally, 27 documents were included in the study, comprising 2 Chinese documents and 25 English documents. The detailed screening process is illustrated in Figure 1.

Sequentially, data extraction was performed by two independent reviewers (MS and LJJ) using the designated data extraction table. The key elements extracted encompassed author and year details, form of sleep deprivation, testing time period, and basic information of the research subjects (including sports items, exercise level, sample size, gender, age), main outcomes. This systematic extraction process aimed to comprehensively capture and organize essential information for subsequent analysis and synthesis.

Data Analysis

The data underwent an analysis using Stata 14.0 Meta-Analysis, employing modules such as "of binary and continuous (matan)" and "Influence Analysis, metan-based" in. The chosen effect size indicator was the standard mean difference (SMD), which categorizes effect size into tiny (below 0.2), small (0.2–0.5), medium (0.5–0.8), and large (above 0.8).[17] The random effects model was applied to merge the data.

To evaluate the quality of the included literature, the Physiotherapy Evidence Database (PEDro) was utilized. Publication bias and sensitivity analyses were conducted using funnel plot and article-by-article removal method. It is crucial to note that in certain performance indicators, larger values correspond to enhanced sporting performance (such as throwing distance, vertical jump height, etc), while in others, smaller values indicate superior sporting performance (such as sprinting grades, etc.). To ensure uniform directionality across all indicators, those with smaller values were uniformly multiplied by "-1" during the data processing.[18] This adjustment guarantees consistency and facilitates a coherent interpretation of the performance outcomes across diverse metrics.

Research Results

Basic Characteristics of Included Literature

This study encompassed a total of 27 papers, comprising 75 sporting performance indicators and involving 369 participants (360 male athletes and 9 female athletes). Among the included documents, 25 focused exclusively on male athletes, while 2 studies included both male and female athletes. The age range of the participants spanned from 15 to 33 years old, and their sports proficiency varied, with high-level athletes accounting for 23.85% and ordinary athletes accounting for 76.15%. The diverse range of sports covered in the study included basketball, football, karate, taekwondo, judo, martial arts, weightlifting, sprinting, cycling, triathlon and tennis. Notably, 8 studies did not specify the sports engaged in by their subjects. The acute sleep deprivation protocols applied in the studies predominantly involved single or dual forms of sleep deprivation (SD, PSDB, PSDE), with certain studies incorporating a washout period to eliminate the influence of the previous form of deprivation in cases where two forms were used. The control group across all studies adhered to a normal sleep routine.

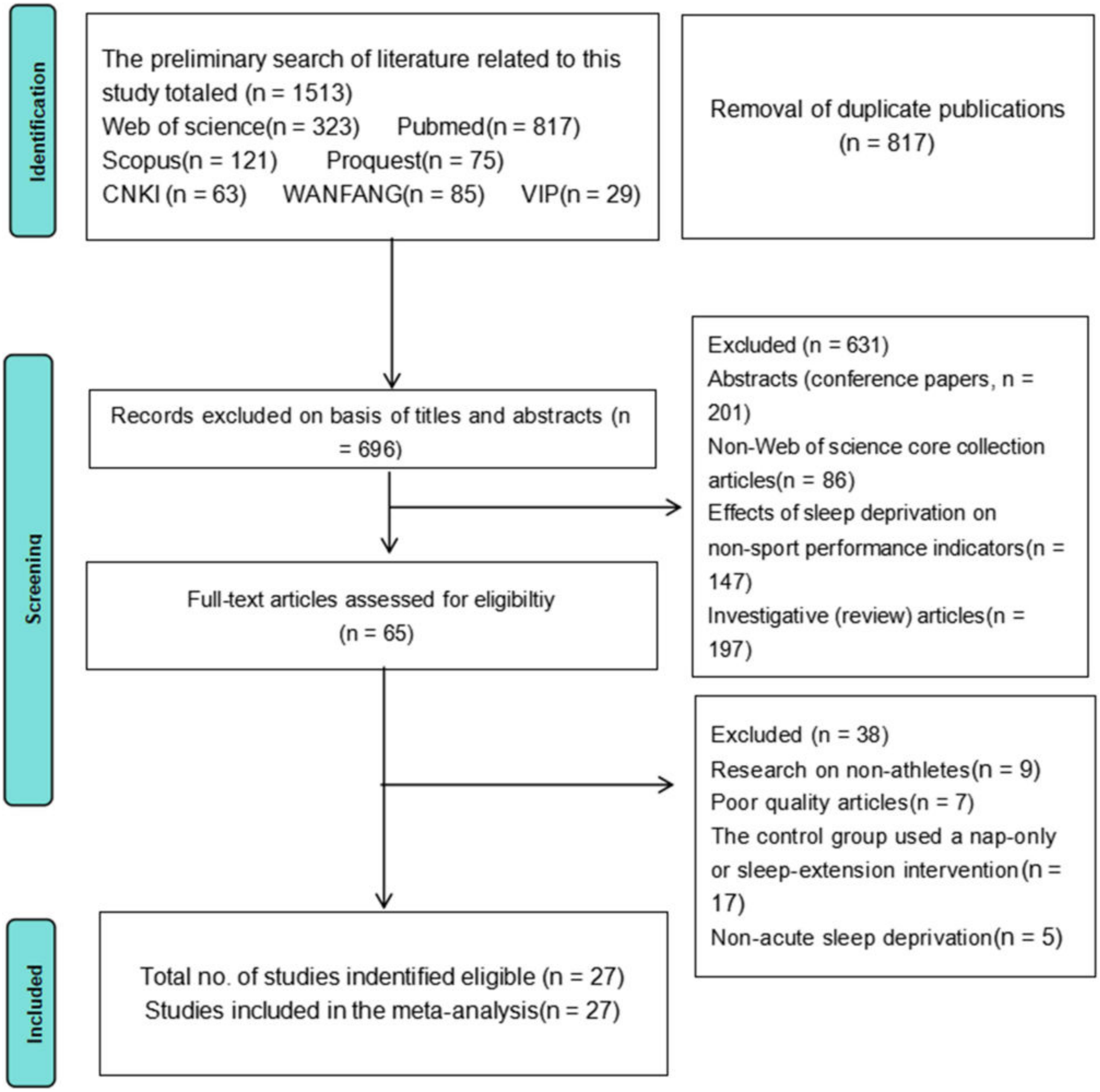

Figure 1 Flow Diagram of Study Selection process. A literature search was performed in core databases (PubMed, Web of Science, etc.). We removed duplicates by NoteExpress reference management software to avoid reviewing duplicate articles. In 1513 publications, 817 publications were excluded. In the final step 38 full articles were excluded mainly as they were less relevant to the topic and research questions than those studies included in the qualitative synthesis, as compared and determined by two authors.

Sporting performance indicators, crucial for accurately reflecting changes in athletes' various abilities post-acute sleep deprivation, varied across studies, primarily contingent on the specific sports undertaken by the participants (Table 1). To enhance precision in exploring the impact of acute sleep deprivation on diverse athletic abilities and facilitate data integration, this study classified indicators based on their energy supply characteristics and neuromuscular working methods during index tests (Table 2). Indicators with short working times, such as vertical jump, squat jump, snatch, and 20m sprint, relying on the phosphate system for energy, were categorized as explosive indicators, reflecting athletes' anaerobic explosive abilities. In contrast, indicators like continuous football kicks, tennis serves, and basketball shots, emphasizing precise control and coordination ability of nerves to muscles were classified as skill control indicators. This classification approach contributes to a nuanced understanding of the nuanced effects of acute sleep deprivation across distinct athletic abilities.

Table 1 Summary of Basic Information of Included Studies

First Author and Year	Intervention Program		Test Period	Basic Information About the Research Subjects					Main Outcome
	Experimental Group	Control Group		Sports Event	Sports Level	Sample Size	Gender	Age	
Mah CD 2019[19]	PSDB 3 nights	RN	Unspecified	Bicycle	High level	11	Male	28.8±4.5	Physical fitness: DVJ.
Pallesen S 2017[20]	SD 1 night	RN	AM	Soccer	Ordinary level	19	Male	16.5±1.3	1. physical fitness: 20 meters sprint, 30 meter changes direction run. 2. soccer: juggling, dribbling, controlling.
Roberts SSH 2019[12]	PSDE 3 nights	RN	AM	Bicycle, triathlon	Ordinary level	9	Male	30±6	Physical fitness: incremental load test and TT test.
Daaloul H 2019[13]	PSDE 1 night	RN	PM	Karate	High level	13	Male	23±2	Physical fitness: SJ, CMJ.
Vitale JA 2021[21]	PSDE 1 night	RN	AM	Tennis	Ordinary level	12	Male	15.4±2.6	1. physical fitness: RSA. 2. tennis: 20 serves each left and right, 15 strokes each forehand and backhand.
Roberts SSH 2019[22]	SD 1 night	RN	AM	Bicycle, triathlon	Ordinary level	13	Male	33±6	Physical fitness: TT test.
Skein M 2011[23]	SD 1 night	RN	PM	Team sports	Ordinary level	10	Male	21±3	Physical fitness:30min step-by-step incremental exercise, sprint, MVC.
Reyner LA 2013[24]	PSDB 1 night	RN	PM	Tennis	Ordinary level	16	Male/ female	18–22	Tennis: 40 serves.
Filipas L 2021[25]	PSDE 1 night	RN	AM	Basketball	Ordinary level	19	Male	20±3	Basketball: 60 shots.
Souissi M 2018[26]	PSDE 1 night	RN	PM	Unspecified	Ordinary level	13	Male	20.7±1.2	Physical fitness:10s Wingate test, 5msrt.
Moore J 2018[7]	SD 1 night	RN	AM	Team sports	Ordinary level	11	Male	25±4	Physical fitness:speed agility test, VJ, 20m sprint, 5msrt.
Romdhani M 2020[27]	PSDE 1 night	RN	PM	Judo	High level	9	Male	18.78±1.09	Physical fitness: RSA.
Souissi N 2013[28]	PSDB 1 night, PSDE 1 night. 7 days apart.	RN	AM/PM	Judo	High level	12	Male	18.6±2.4	Physical fitness: HG, MVC, Wingate test.
Ben Cheikh R 2017[9]	SD 1 night	RN	AM	Karate	Ordinary level	12	Unspecified	16.9±0.8	Physical fitness: MVC and duration.
Cullen T 2019[29]	SD 1 night, PSDE 1 night. 7 days apart.	RN	AM	Unspecified	Ordinary level	10	Male	27±6	Physical fitness: HG, CMJ, 15min self-paced ride.
Taheri M 2012[8]	SD 1 night	RN	AM	Unspecified	Ordinary level	18	Male	22±1.12	Physical fitness: Wingate test.
Blumert PA 2007[30]	SD 1 night	RN	AM	Weightlifting	High level	9	Male	20.7±1.2	Weightlifting: snatch, clean and jerk, deep squat in front of the neck.
Vardar SA 2007[31]	SD 1 night, PSDB 1 night. 14 days apart.	RN	PM	Unspecified	Ordinary level	13	Male	22±1.12	Physical fitness: Wingate test.

(*Continued*)

Table 1 (Continued).

First Author and Year	Intervention Program		Test Period	Basic Information About the Research Subjects					Main Outcome
	Experimental Group	Control Group		Sports Event	Sports Level	Sample Size	Gender	Age	
Oliver SJ 2009[32]	SD 1 night	RN	PM	Unspecified	Ordinary level	11	Male	20±3	Physical fitness: 30min predetermined load run (60% VO_2max), 30min self-paced run.
Mejri MA 2014[11]	PSDB 1 night, PSDE 1night. 1.5 days apart.	RN	AM	Karate	High level	10	Male	17.6±0.52	Physical fitness: Yo-Yo intermittent test.
Souissi M 2020[33]	PSDE 1 night	RN	PM	Unspecified	Ordinary level	14	Male	20.5±1.5	Physical fitness: 5msrt.
Abedelmalek S 2013[34]	PSDE 1 night	RN	AM/PM	Soccer	Ordinary level	12	Male	21.2±1.5	Physical fitness: Wingate test.
Chase JD 2017[10]	PSDE 1 night	RN	AM	Bicycle	Ordinary level	7	Male/ female	24±7	Physical fitness: 3km timed (TT), maximal isokinetic torque test.
Xiaodan N 2022[35]	PSDB 1 night	RN	AM	Unspecified	Ordinary level	30	Male	21.97±2.14	Physical fitness: Bruce exercise program.
Yue Z 2022[36]	PSDB 1 night	RN	AM	Unspecified	Ordinary level	20	Male	20.74±3.68	Physical fitness: Bruce exercise program.
Khcharem A 2022[37]	SD 1 night	RN	AM	Track and field	Ordinary level	12	Male	21.7±0.9	Physical fitness: TTE.
Saddoud A 2022[38]	SD 1 night	RN	PM	Martial arts	High level	24	Male	20.2±1.76	Physical fitness: seated medicine ball throwing, DVJ, MVC.

Note: ordinary level: Trained/Developmental (Regularly training −3 times per week / Training with a purpose to compete / Identify with a specific sport / Limited skill development).

Abbreviations: DVJ, Drop Maximal Vertical Jumps; TT, Time-Trial, timed running (riding); SJ, Squat Jump; CMJ, Counter Movement Jump; RSA, Repeated Sprint Ability Test; MVC, Maximal Isometric Voluntary Contraction; 5msrt, 5-metre Shuttle Run Test; VJ, Vertical Jumps; HG, Handgrip Strength; Wingate: Wingate test; TTE, Time To Exhaustion; SD, Whole night sleep deprivation; PSDB, partial sleep deprivation in the beginning of the night; PSDE, partial sleep deprivation at the end of the night; RN, reference normal sleep night, normal sleep; AM, Ante Meridiem, morning; PM, Post Meridiem, afternoon; VO2max, Maximal Oxygen Consumption.

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Table 2 Types and Main Characteristics of Sports Performance Indicators Included in the Literature

Exercise Category	Main Characteristic	Example Task
Explosive power	Phosphate system energy supply	MVC, CMJ, SJ, Wingate peak power, HG, VJ, 20m sprint
Speed	Combined energy supply of the phosphagen and glycolytic systems	Wingate average power, 5msrt peak distance, RAS peak power (distance)
High-intensity intermittent exercise	Combined energy supply by the glycolytic and aerobic oxidative systems	3km-TT, Yo-Yo test total distance, 5msrt total distance, RAS total time
Aerobic endurance	Aerobic oxidation system for energy supply	TTE, 30min endurance running
Skill Control	Precise innervation of muscles by the nerves	Juggling, Serve, shooting, etc.

Abbreviations: MVC, Maximal Isometric Voluntary Contraction; CMJ, Counter Movement Jump; SJ, Squat Jump; Wingate, Wingate test; HG, Handgrip Strength; VJ, Vertical Jumps; 5msrt, 5-metre Shuttle Run Test; RSA, Repeated Sprint Ability Test; 3km-TT, 3-kilometer timed ride; TTE, Time to Exhaustion.

Literature Quality Assessment, Publication Bias Test, and Sensitivity Analysis

The quality of the included literature was evaluated using PEDro. The assessment revealed that 25 articles in this study achieved a PEDro score of ≥6 points, with an average score of 6.39 points (Supplementary File 2). This indicates a high level of quality among the included documents.

The publication bias, depicted through the funnel plot, illustrates that the majority of documents are evenly distributed near the central axis. This uniform distribution suggests an absence of obvious publication bias, reinforcing the reliability of the findings.

Sensitivity analysis, employing the article-by-article removal method, was conducted on the included literature, recalculating the confidence interval range. The results demonstrated that, upon systematically removing each article, all outcomes remained within the original 95% CI, without substantial changes. This underscores the stability and credibility of the analyzed results in this study, reaffirming the robustness of the findings.

The Overall Impact of Acute Sleep Deprivation on Athletes' Sporting Performance

Overall, this study comprehensively examined 75 sporting performance indicators, revealing an overall effect size of acute sleep deprivation on athletes' sporting performance (d=−0.56, $P<0.001$, 95% CI=[−0.74, −0.38]). This effect size reached a medium level, signifying a statistically significant reduction in athletes' overall sporting performance due to acute sleep deprivation (Table 3) (Supplementary File 3).

Examining various subtypes of acute sleep deprivation reveals distinct effects on athletes' sporting performance. Within the SD group, comprising 27 indicators, the effect size (d) was −0.23 ($P=0.003$, 95% CI = [−0.38, −0.08]). This denotes a small effect size level that is statistically significant, indicating a reduction in athletes' sporting performance with SD (Supplementary File 4).

In contrast, the PSDB group encompassing 16 indicators exhibited an effect size (d) of −0.25, with a 95% CI = [−0.53, 0.04]. Despite a decrease in athletes' sporting performance associated with PSDB, the result was not statistically significant ($P > 0.05$) (Supplementary File 5).

Table 3 Effects of Acute Sleep Deprivation on Athletes' Sporting Performance

Sleep-Loss Condition	Outcomes, n	Effect (95% CI)	*P* value
SD	27	−0.23 (−0.38, −0.08)	0.003
PSDB	16	−0.25 (−0.53, 0.04)	0.095
PSDE	32	−1.17 (−1.56, −0.78)	<0.001
Over all	75	−0.56 (−0.74, −0.38)	<0.001

Abbreviations: SD, Whole night sleep deprivation; PSDB, partial sleep deprivation in the beginning of the night; PSDE, partial sleep deprivation at the end of the night.

The PSDE group including 32 indicators demonstrated a substantial effect size (d) of −1.17 (P<0.001, 95% CI = [−1.56, −0.78]), surpassing the large effect size level. The significant result underscores that PSDE can markedly reduce athletes' sporting performance (Supplementary File 6).

Effects of Acute Sleep Deprivation on Different Types of Sporting Performance

Table 4 provides an overview of 39 indicators in the explosive power group, revealing an overall effect size of d = −0.39 (P<0.001, 95% CI = [−0.60, −0.18]). Acute sleep deprivation subtypes were further scrutinized, unveiling that PSDE had the most pronounced negative impact on athletes' explosive power (d = −0.95, P<0.001, 95% CI = [−1.47, −0.43]), reaching a large effect size level. SD exhibited a lesser negative effect (d = −0.23, P=0.017, 95% CI = [−0.42, −0.04]). As the effect size of the PSDB group was not statistically significant (P>0.05), it is evident that both SD and PSDE can reduce the explosive power performance of athletes.

In the speed group, encompassing 14 indicators, the overall effect size was d=−0.67 (P=0.029, 95% CI = [−1.27, −0.07]). Subgroup analysis emphasized the substantial negative impact of PSDE (d=−1.81, P=0.002, 95% CI = [−2.93, −0.68]), exceeding the large effect size level. Conversely, the effect sizes of the SD and PSDB groups were not statistically significant (P>0.05), affirming that PSDE significantly diminishes athletes' speed performance.

The high-intensity intermittent exercise group, comprising 5 indicators, demonstrated an overall effect size of d= −1.57 (P=0.024, 95% CI = [−2.93, −0.20]). PSDE exhibited a more pronounced negative impact (d=−2.01, P=0.02, 95% CI = [−3.70, −0.31]), surpassing the large effect size level. As the effect size of the PSDB group was not statistically significant (P>0.05), and the SD group lacked relevant indicators, it is evident that PSDE significantly reduces the high-intensity intermittent sporting performance of athletes.

Within the aerobic endurance group, including 11 indicators, the overall effect size was d=−0.54 (P<0.001, 95% CI = [−0.79, −0.29]). Subgroup analysis highlighted that both the SD group and the PSDB group exhibited statistically

Table 4 Effects of Acute Sleep Deprivation on Different Types of Sporting Performance

Exercise Category	Sleep-Loss Condition	Outcomes, n	Effect (95% CI)	*P* value
Explosive power	Over all	39	−0.39 (−0.60, −0.18)	<0.001
	SD	16	−0.23 (−0.42, −0.04)	0.017
	PSDB	8	−0.05 (−0.33, 0.24)	0.75
	PSDE	15	−0.95 (−1.47, −0.43)	<0.001
Speed	Over all	14	−0.67 (−1.27, −0.07)	0.029
	SD	4	0.24 (−0.14, 0.63)	0.214
	PSDB	3	0.13 (−0.33, 0.58)	0.59
	PSDE	7	−1.81 (−2.93, −0.68)	0.002
High-intensity intermittent exercise	Over all	5	−1.57 (−2.93, −0.20)	0.024
	SD	—	—	—
	PSDB	1	−0.05 (−0.93, 0.82)	0.91
	PSDE	4	−2.01 (−3.70,-0.31)	0.02
Aerobic endurance	Over all	11	−0.54 (−0.79, −0.29)	<0.001
	SD	6	−0.56 (−0.94, -0.18)	0.004
	PSDB	2	−0.64 (−1.12, −0.16)	0.01
	PSDE	3	−0.37 (−0.92, 0.18)	0.18
Skill Control	Over all	6	−1.06 (−1.72, −0.40)	0.002
	SD	1	−0.38 (−1.02, 0.26)	0.247
	PSDB	2	−1.31 (−3.08, 0.46)	0.15
	PSDE	3	−1.16 (−2.12, −0.19)	0.019

Notes: There are no relevant sporting performance indicators in the sleep deprivation subgroup of high-intensity intermittent exercise, so the number of indicators, effect values, and 95% CI and *P* values of this group are all marked with "—".
Abbreviations: SD, Whole night sleep deprivation; PSDB, partial sleep deprivation in the beginning of the night; PSDE, partial sleep deprivation at the end of the night.

significant medium effect sizes (d = −0.56, *P*=0.004; d = −0.64, *P*=0.01, respectively), with 95% CI of [−0.94, −0.18] and [−1.12, −0.16], respectively. Conversely, the effect size of the PSDE group was not statistically significant (*P*>0.05), indicating that both SD and PSDB significantly diminish the aerobic endurance performance of athletes.

Lastly, in the skill control group, consisting of 6 indicators, the overall effect size was d=−1.06 (*P* = 0.002, 95% CI = [−1.72, −0.40]). PSDE exhibited a significant negative impact (d = −1.16, *P* = 0.019, 95% CI = [−2.12, −0.19]), surpassing the large effect size level. As the effect sizes of the SD and PSDB groups were not statistically significant (*P*>0.05), it is evident that PSDE significantly diminishes the sporting performance of athletes' skill control.

Sporting Performance Tested at Different Time Periods After Acute Sleep Deprivation

In the AM test group, encompassing a total of 43 indicators, the overall effect size was d=−0.30 (*P*<0.001, 95% CI = [−0.43, −0.16]), representing a small effect size level. Conversely, the PM test group, comprising 30 indicators, exhibited an overall effect size of −1.11 (*P*<0.001, 95% CI = [−1.53, −0.69]), surpassing the large effect size level (Table 5). This indicates a significant reduction in athletes' sporting performance in both AM and PM of the next day after acute sleep deprivation, with a more pronounced decline observed in the PM (*P*<0.05) (Supplementary Files 7 and 8).

Various athletic performance indicators also demonstrated differing degrees of variation between the AM and PM tests. In the AM test, the effect sizes of explosive power, speed, and high-intensity intermittent exercise were −0.16, 0.10, and −0.34, respectively, with 95% CI of [−0.34, 0.02], [−0.22, 0.42] and [−0.84, 0.16], respectively. These results were not statistically significant (*P*>0.05). However, the effect sizes of aerobic endurance and skill control indicators were −0.62 (*P*<0.001) and −0.93 (*P*=0.011), respectively, with 95% CI of [−0.89, −0.34] and [−1.64, −0.22], respectively, indicating a significant drop in athletes' aerobic endurance and skill control indicators in the AM test following acute sleep deprivation (Supplementary File 7).

In the PM test, the effect sizes of the high-intensity intermittent exercise and aerobic endurance indicators were −3.85 and −0.18, respectively, with 95% CI of [−8.12, 0.41] and [−0.78, 0.43], respectively. These results were not statistically significant (*P*>0.05). However, the effect sizes of explosive power, speed and skill control were −0.77 (*P*=0.001), −1.47 (*P*=0.007), and −2.22 (*P*<0.001) respectively, with 95% CI of [−1.21, −0.33], [−2.53, −0.40] and [−3.11, −1.33]. These findings indicate a significant decline in athletes' explosive power, speed, and skill control in the PM test following acute sleep deprivation. It is noteworthy that in both AM and PM tests, skill control indicators significantly greater decline compared to other indicators, emphasizing the substantial impact of acute sleep deprivation on these specific performance measures (Supplementary Files 1-6).

Discussion

Mechanisms of Acute Sleep Deprivation Impacting Athletes' Sporting Performance

Acute sleep deprivation demonstrates a significant reduction in the overall sporting performance of athletes, yielding a medium effect size level (−0.56). This aligns with the findings of Craven's study.[39] The analysis suggests that the impact of acute sleep deprivation on athletes' sporting performance may be attributed to several factors. Firstly, there is

Table 5 Effects of Sporting Performance Tested at Different Time Periods After Acute Sleep Deprivation

Exercise Category	**AM**			**PM**		
	Effect (95% CI)	**Outcomes, n**	***P* value**	**Effect (95% CI)**	**Outcomes, n**	***P* value**
Explosive power	−0.16 (−0.34, 0.02)	21	0.082	−0.77 (−1.21, −0.33)	17	0.001
Speed	0.10 (−0.22, 0.42)	6	0.536	−1.47 (−2.53, −0.40)	8	0.007
High-intensity intermittent exercise	−0.34 (−0.84, 0.16)	3	0.181	−3.85 (−8.12, 0.41)	2	0.076
Aerobic endurance	−0.62 (−0.89, −0.34)	9	<0.001	−0.18 (−0.78, 0.43)	2	0.569
Skill Control	−0.93 (−1.64,−0.22)	4	0.011	−2.22 (−3.11, −1.33)	1	<0.001
Over all	−0.30 (−0.43, −0.16)	43	<0.001	−1.11 (−1.53, −0.69)	30	<0.001

Abbreviations: AM, Ante Meridiem, morning; PM, Post Meridiem, afternoon.

a correlation with the depletion of the body's energy reserves. Acute sleep deprivation of athletes increases energy consumption to sustain physiological functions during wakefulness while impeding the resynthesis of energy substances post-exercise. Consequently, this leads to a decline in muscle glycogen and liver glycogen reserves, impacting the body's mobilization efficiency and maintenance ability during exercise.[23] Secondly, the reduction in athletes' cognitive function due to sleep deprivation may play a significant role. This encompasses impairments in working memory, response inhibition, attention function and executive function. The literature provides theoretical explanations for the impact of sleep deprivation on cognitive functions, including attention control, alertness, prefrontal cortex susceptibility, and neuropsychological aspects.[40] The third potential mechanism involves the inflammatory response triggered by acute sleep deprivation. The repair of the human immune system, primarily occurring during slow wave sleep (SWS), is hindered by sleep deprivation, leading to the prolongation of rapid eye movement sleep (REM) and disruptions in sleep structure. Thereby, the increasing levels of inflammatory factors like interleukin-6, C-reactive protein, and tumor necrosis factor-α. These factors contribute to a reduction in the body's exercise capacity.[41]

Research findings indicate that different types of acute sleep deprivation exert distinct effects on athletes' sporting performance. Specifically, PSDE exhibits the most substantial negative impact (effect size −1.17), followed by SD (effect size −0.23). The effect size of PSDB is not statistically significant. Zerouali's research supports that PSDE has a more pronounced impact on athletes' selective attention than PSDB, possibly due to its influence on REM and SWS, critical stages for attention restoration and various physiological functions (such as memory consolidation, immune repair, energy recovery, and hormone release).[42,43]

Examining the impact of different acute sleep deprivation types on various sporting performance indicators, PSDE, significantly affects explosive power, speed, high-intensity intermittent exercise, and skill control indicators (effect sizes are −0.95, −1.81, −2.01, −1.16 respectively), surpassing the impact of SD. This may be associated with the emotional arousal level of athletes before these tests. Athletes undergoing PSDE exhibit lower emotional arousal and a tendency towards depression,[44] while SD induces higher emotional arousal, anxiety and mania. Therefore, explosive power, speed, high-intensity intermittent exercise, and skill control indicators are less affected by SD in comparison.

Analysis of the Impact of Acute Sleep Deprivation on Different Types of Sporting Performance

Acute sleep deprivation significantly impairs various types of sporting performance, with distinct magnitudes of impact across indicators. Examining effect sizes reveals that high-intensity intermittent exercise and skill control indicators experience the most substantial negative effects (−1.57, −1.06, respectively), followed by speed and aerobic endurance indicators (−0.67, −0.54 respectively), while explosive power indicators are relatively less affected by acute sleep deprivation (−0.39).

The significant impact of high-intensity intermittent exercise indicators may be attributed to alterations in athletes' Rating of Perceived Exertion (RPE), reflecting their perceived effort during tasks. When athletes feel that the effort required to complete a task exceeds their maximum potential, their willingness and efficiency to continue working will decrease.[22] Acute sleep deprivation alters the body's fatigue perception, resulting in increased subjective fatigue during exercise of the same intensity.[21] Athletes' perception of fatigue during high-intensity exercise is notably higher than during moderate-intensity exercise.[32]

The decline in skill control sporting performance is linked to impaired executive functions post-sleep deprivation, affecting dimensions such as working memory, inhibitory control, and cognitive flexibility.[45] Evidence indicates behavioral manifestations of prolonged reaction times, increased error rates, and decreased accuracy after acute sleep deprivation.[20,25] At the neural level, weakened activation of the attention network and salience network, along with altered antagonistic connections, influences cognitive resource ability.[6] The theoretical hypothesis suggests a link between decreased testosterone levels and dopamine regulation, confirmed in animal studies.[25]

Reduced speed and aerobic endurance indicators may be related to the working hours and energy supply characteristics. Speed indicators reflect greater intensity, longer duration, and glycolysis energy supply during work, while aerobic endurance indicators involve lower intensity, longer duration (usually over 30 minutes), and mainly aerobic energy supply during work. Therefore, the reserve amount of energy substances and the resynthesis ability of energy substances during work are the keys to affect the sporting performance of these two indicators. Acute sleep deprivation increases energy consumption, leading to decreased muscle and liver glycogen, affecting the body's ability to resynthesize energy substances during exercise.[23]

Inflammatory factors such as interleukin-6 increase during acute sleep deprivation, altering hormone balance, and inducing inflammation and proteolysis, impacting muscle structure and function.[46] This negatively affects explosive power indicators, although to a lesser extent. The shorter duration and reliance on the phosphagen system for explosive power indicators contribute to athletes maintaining motivation and synthesizing energy substances efficiently during exercise.

Analysis of Differences in Sporting Performance Between AM and PM After Acute Sleep Deprivation

Acute sleep deprivation exhibits a minor impact on athletes' overall sporting performance in AM (−0.30), but exerts a more pronounced influence on overall sporting performance in PM (−1.11). Examining specific indicators reveals a significant decline in aerobic endurance and skill control indicators during the AM test (effect sizes were −0.62 and −0.93 respectively), while explosive power, speed, and skill control indicators experience substantial drops in the PM (effect sizes were −0.77, −1.47, −2.22, respectively). For example, a football player undergoing acute sleep deprivation may not witness significant changes in peak power and average power in the Wingate test the next morning, but both indicators significantly reduce in the PM test. Cullen's findings corroborate this, indicating that the handgrip strength remains relatively stable in the morning but diminishes significantly in the PM.[29] It is noteworthy that skill control indicators are most profoundly affected by acute sleep deprivation, demonstrating significant declines in both AM and PM tests.

Analysis suggests that mental fatigue induced by prolonged awakening and alterations in athletes' perception of fatigue could contribute significantly to their overall diminished performance in the afternoon. Athletes may experience mental fatigue following prolonged wakefulness, akin to neuromuscular fatigue. This can not only diminish the body's alertness and alter physical energy output but also impair movement control accuracy and influence neuromuscular coordination strategies at work.[19] After acute sleep deprivation, changes in athletes' perception of fatigue become evident, equating the fatigue experienced after short-term, low-intensity exercise to that of long-term, moderate-intensity exercise pre-sleep deprivation. As a result, athletes' ability to perform medium-to-high-intensity exercises such as explosive power and speed diminishes.[34] Notably, athletes' aerobic endurance performance in the afternoon improves after acute sleep deprivation, potentially linked to elevated core body temperature and enhanced efficiency of the aerobic energy supply system in the afternoon.[28]

From a mechanistic perspective, sustained arousal can lead to a delay in the body's circadian rhythm, altering the normal working mechanism of muscle cells and affecting the physiological function of muscle contraction and relaxation. Circadian rhythm changes, such as variations in inorganic phosphate concentration or core body temperature, impact the release of calcium ions from the sarcoplasmic reticulum, influencing muscle strength within a certain range. Additionally, the decline in athletes' overall sporting performance in the PM may be related to the body's sleep homeostasis regulation. As waking time extends, sleep pressure gradually increases, resulting in sleep debt. To rectify this sleep debt, the body actively enters sleep, reducing work efficiency. The accumulation of adenosine in the brain serves as the physiological basis for sleep homeostasis regulation. As the waking time prolongs, adenosine concentration gradually increases, inhibiting the excitement of orexin neurons and the activity of dopamine neurons in the hypothalamus, consequently diminishing the body's sporting performance.[47] In addition, malabsorption can impair the absorption of key nutrients that are essential for energy production, muscle function, and cognitive performance, potentially worsening the adverse effects of sleep deprivation.[48,49]

Limitations

This study is constrained by the quantity and quality of available original research literature. Some subgroups, such as the afternoon period of the aerobic endurance group, have limited data, incorporating only 2 indicators post-acute sleep deprivation. Further investigation is needed to ascertain whether the relatively small number of indicators in this subgroup contributes to the observed improvement in afternoon aerobic endurance performance compared to the morning. Moreover, in the process of outcome indicator extraction, our study focused exclusively on sporting performance and employed a classification primarily based on the energy supply characteristics and neuromuscular working methods. The potential existence of a more scientifically rigorous classification method warrants further exploration and scrutiny. Future research endeavors could delve into refining the methodology for a more nuanced categorization of outcome indicators.

Conclusions

Acute sleep deprivation significantly hampers athletes' overall sporting performance, with the most profound negative impact observed in the context of PSDE.

Various facets of sporting performance are adversely affected by acute sleep deprivation, with the following order of impact: high-intensity intermittent exercise, skill control, speed, aerobic endurance, and explosive power.

Post-acute sleep deprivation, athletes' overall sporting performance demonstrates a more pronounced decline in the PM compared to the AM. Specifically, aerobic endurance experiences a significant decrease in the AM, while explosive power and speed exhibit notable reductions in the PM. Moreover, skill control demonstrates a significant decrease in both the AM and PM.

Practice Points

1. Strategic optimization and adjustment of training schedules based on the varying impact of acute sleep deprivation on different exercise abilities are crucial for achieving optimal training outcomes.
2. For sports emphasizing explosive power, speed, skill control, and similar attributes, consider reducing the time interval between awakening and training (or competition) to mitigate the negative effects of acute sleep deprivation.
3. In unavoidable situations of acute sleep deprivation, athletes may prefer PSDB, such as traveling the night before, over PSDE involving early morning travel. This choice can potentially yield more effective mitigation of the adverse effects associated with acute sleep deprivation.

Author Contributions

All authors made a significant contribution to the work reported, whether that is in the conception, execution, acquisition of data, analysis and interpretation, or in all these areas; took part in drafting, revising or critically reviewing the article; gave final approval of the version to be published; have agreed on the journal to which the article has been submitted; and agree to be accountable for all aspects of the work.

Disclosure

The authors declare that they have no competing interests in this work.

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