SYSTEMATIC REVIEW

Effects of Acute Sleep Loss on Physical Performance: A Systematic and Meta-Analytical Review

Jonathan Craven[1,2] · Danielle McCartney[3] · Ben Desbrow[1] · Surendran Sabapathy[1] · Phillip Bellinger[1,4] · Llion Roberts[1,4,5] · Christopher Irwin[1]

Abstract

Background Sleep loss may influence subsequent physical performance. Quantifying the impact of sleep loss on physical performance is critical for individuals involved in athletic pursuits.

Design Systematic review and meta-analysis.

Search and Inclusion Studies were identified via the Web of Science, Scopus, and PsycINFO online databases. Investigations measuring exercise performance under 'control' (i.e., normal sleep, > 6 h in any 24 h period) and 'intervention' (i.e., sleep loss, ≤ 6 h sleep in any 24 h period) conditions were included. Performance tasks were classified into different exercise categories (anaerobic power, speed/power endurance, high-intensity interval exercise (HIIE), strength, endurance, strength-endurance, and skill). Multi-level random-effects meta-analyses and meta-regression analyses were conducted, including subgroup analyses to explore the influence of sleep-loss protocol (e.g., deprivation, restriction, early [delayed sleep onset] and late restriction [earlier than normal waking]), time of day the exercise task was performed (AM vs. PM) and body limb strength (upper vs. lower body).

Results Overall, 227 outcome measures (anaerobic power: $n = 58$; speed/power endurance: $n = 32$; HIIE: $n = 27$; strength: $n = 66$; endurance: $n = 22$; strength-endurance: $n = 9$; skill: $n = 13$) derived from 69 publications were included. Results indicated a negative impact of sleep loss on the percentage change ($\%_\Delta$) in exercise performance ($n = 959$ [89%] male; mean $\%_\Delta = -7.56\%$, 95% CI -11.9 to -3.13, $p = 0.001$, $I^2 = 98.1\%$). Effects were significant for all exercise categories. Subgroup analyses indicated that the pattern of sleep loss (i.e., deprivation, early and late restriction) preceding exercise is an important factor, with consistent negative effects only observed with deprivation and late-restriction protocols. A significant positive relationship was observed between time awake prior to the exercise task and $\%_\Delta$ in performance for both deprivation and late-restriction protocols (~ 0.4% decrease for every hour awake prior to exercise). The negative effects of sleep loss on different exercise tasks performed in the PM were consistent, while tasks performed in the AM were largely unaffected.

Conclusions Sleep loss appears to have a negative impact on exercise performance. If sleep loss is anticipated and unavoidable, individuals should avoid situations that lead to experiencing deprivation or late restriction, and prioritise morning exercise in an effort to maintain performance.

✉ Jonathan Craven
  jonathan.craven@griffithuni.edu.au

1 School of Health Sciences and Social Work, Griffith University, Southport, QLD 4222, Australia

2 Queensland Academy of Sport, Nathan, QLD, Australia

3 School of Psychology, Faculty of Science, University of Sydney, Sydney, NSW, Australia

4 Griffith Sports Science, Griffith University, Gold Coast, QLD, Australia

5 School of Human Movement and Nutrition Sciences, University of Queensland, Brisbane, QLD, Australia

1 Introduction

Sleep is essential to maintain physical and mental health. It has been shown to promote memory [1], regulate emotions [2], enhance metabolic functions [3], improve energy balance, and moderate the immune system [4], and may play a pivotal role in the stress–recovery balance, via its influence on the activity of the hypothalamic–pituitary–adrenal axis [5]. Despite this knowledge, ~ 45% of the Western adult population fail to obtain the recommended 7–9 h of sleep each night [6]. Sleep loss is often driven by lifestyle choices that reduce available sleep time, such as evening social

Key Points

Acute sleep loss negatively impacts next-day exercise performance

The magnitude and significance of the impact are dependent on the sleep-loss protocol preceding exercise, with sleep deprivation and late-restriction (earlier than normal waking) protocols demonstrating a consistent negative influence

The time awake prior to performing exercise was found to be an influential factor

Exercise tasks performed in the PM were consistently negatively affected by sleep loss, while tasks performed in the AM were largely unaffected

activities [7], exposure to artificial light prior to sleep [8], consumption of caffeinated beverages [9], and smoking [10]. Stress and anxiety [11], medical conditions/illness [12], and genetic traits [13, 14] can also contribute to sleep loss. Certain populations, including professional athletes [15–24], shift workers [25] and military personnel [26], appear particularly susceptible to sleep loss. For athletes, sleep loss may be exacerbated by early morning training sessions [27, 28], training or competing at altitude (> 2000 m) [29], travel (late night and early morning departures) [30, 31], and the use of caffeine as an ergogenic aid [32].

Insufficient sleep can result in a significant personal and societal burden, including adverse effects on wellbeing [33], productivity [34] and safety [35]. For those who are physically active or involved in athletic pursuits, sleep loss may also influence acute training adaptations and exercise performance outcomes [17, 36, 37]. The consequences of sleep loss (e.g., altered training adaptations, increased workplace accidents [38, 39]) are likely to have multiple aetiologies. Negative consequences may result from a decrease in muscular strength [40] and/or endurance [41], change in mood (e.g., decreased motivation) [42], an increase in perceived effort [43, 44], changes to cognitive processing ability (e.g., decision making, executive function) and/or a reduction in fine motor skills [45], or a combination of these factors.

Sleep has two distinct dimensions: quantity and quality. However, sleep loss is more often measured in terms of duration, given the challenges associated with accurately determining sleep quality in most situations [46]. Sleep deprivation is a general term used to describe a period of extended wakefulness, often related to circumstances when

an individual is unable to obtain any sleep across a period of ≥ 24 h [47]. Restricted sleep (also referred to as 'partial sleep deprivation') occurs when an individual has the opportunity to sleep, but this is limited in duration from their normal sleep habit [47] and is often a result of delayed sleep onset (sometimes termed 'early restriction'), earlier than normal waking (sometimes termed 'late restriction'), or fragmented sleep, which is when one or more nocturnal awakenings occur [48] (Fig. 1 depicts the different types of sleep loss). The amount (e.g., deprivation/restriction) and type (e.g., early restriction/late restriction) of sleep loss incurred may have some influence on the magnitude of effect that insufficient sleep has on physical performance [49–52].

The influence of sleep loss on physical performance has received considerable scientific attention. Studies have investigated the effects of sleep loss on performance in different exercise tasks (based on predominant physical attributes), including strength [41, 53–55], anaerobic power/capacity [56–62], endurance [41, 57], and those requiring a high level of precision (e.g., skill activities [45, 63]). The influence of contextual factors has also been explored, including the timing of exercise following sleep loss (e.g., morning vs. evening exercise) [45, 53, 62, 64]; duration of sleep loss [65]; early- vs. late-sleep restriction protocols [66, 67]; and exercise characteristics themselves (acute, chronic, type and timing) [64, 68, 69]. While several reviews have summarised these effects [36, 70, 71], only one employed meta-analytical techniques to synthesise the outcomes [72]. However, this particular review was conducted over two decades ago, and many studies conducted since have improved our understanding of sleep loss and its impact on physical performance.

Therefore, the aim of this systematic review was to summarise the available literature investigating the effects of acute sleep loss (≤ 6 h sleep in any 24 h period) on exercise performance and quantify the magnitude of effects using meta-analytical techniques. The influence of certain contextual factors (e.g., exercise type, time of day, sleep-loss duration) was also explored.

2 Methods

The methodology of this review was developed in accordance with the Preferred Reporting Items for Systematic Reviews and Meta-Analysis Protocols 2015 statement [73] and registered at the International Prospective Register of Systematic Reviews (PROSPERO; identification code: CRD42020211824).
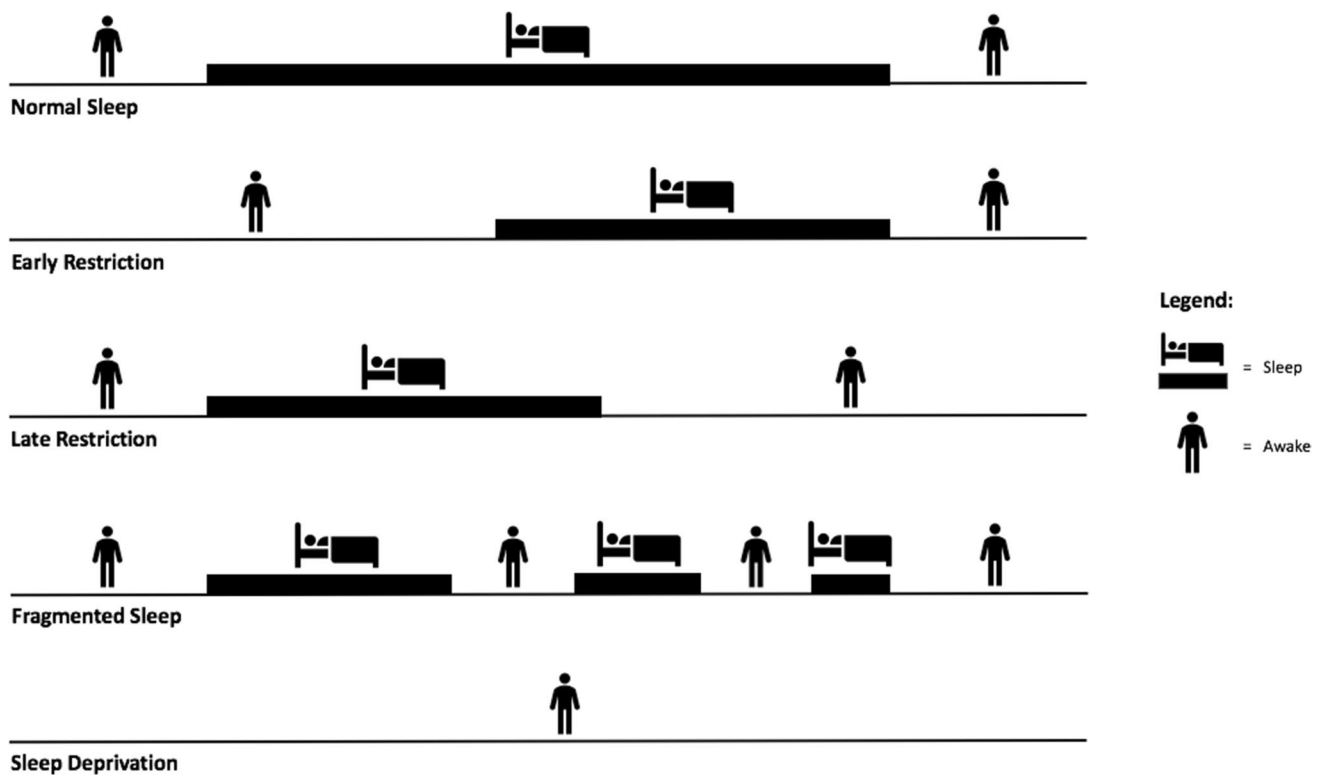
Fig. 1 Types of sleep loss encountered

2.1 Literature Search

Studies were identified by searching the Web of Science (via Thomas Reuters), Scopus, and PsycINFO online databases from inception until September 2020 using the Boolean expression: (sleep restriction OR sleep deprivation OR sleep loss OR wakefulness) AND (exercis* OR performance AND NOT animal* OR rat* OR mice). The star symbol (*) was used to capture derivatives (by suffixation) of the search terms. Two investigators (JC and CI) independently screened the potential publications to identify relevant texts. Initially, all irrelevant titles were discarded. The remaining publications were then systematically screened for eligibility by abstract and full text. The decision to include or discard potential publications was made between two investigators (JC and CI) and any discrepancies were resolved in consultation with a third investigator (DM). One investigator (JC) also hand-searched the reference lists of included publications and performed a forward citation search of two previous systematic reviews [36, 71] to ensure all relevant publications were captured. An updated search was also conducted on 31 December 2021 to capture the most recent publications. Full details of the screening process are illustrated in Fig. 2.

2.2 Inclusion and Exclusion Criteria

Original research studies that met the following criteria were included in this review: (1) full-text original articles written in English; (2) controlled trials employing repeated measures experimental designs; (3) human studies on adult (≥ 18 years of age) men and women with no known medical conditions and comorbidities; and (4) measured performance on an exercise/physical task (e.g., Wingate test, squat jump) under 'sleep loss' (i.e., ≤ 6 h sleep in any 24 h period) and 'control' (i.e., normal sleep, considered as > 6 h in any 24 h period) conditions.

Studies were excluded from the review if (1) a between-subject experimental design was employed and no baseline measurements were performed following 'normal sleep'; (2) sleep-loss protocol was not 'acute' (i.e., it was sustained over multiple nights); (3) stimulants or sedatives were administered (e.g., caffeine, L-tryptophan, or modafinil) during the trial; (4) exercise prior to sleep intervention was not matched across conditions;[1] (5) participants reported abnormal sleep

---

[1] Goh et al. [55] undertook two additional hand-grip strength measurements during the sleep deprivation arm of the study that were not matched in the control arm; this was deemed likely to not have an influence, and was thus included in the analysis.
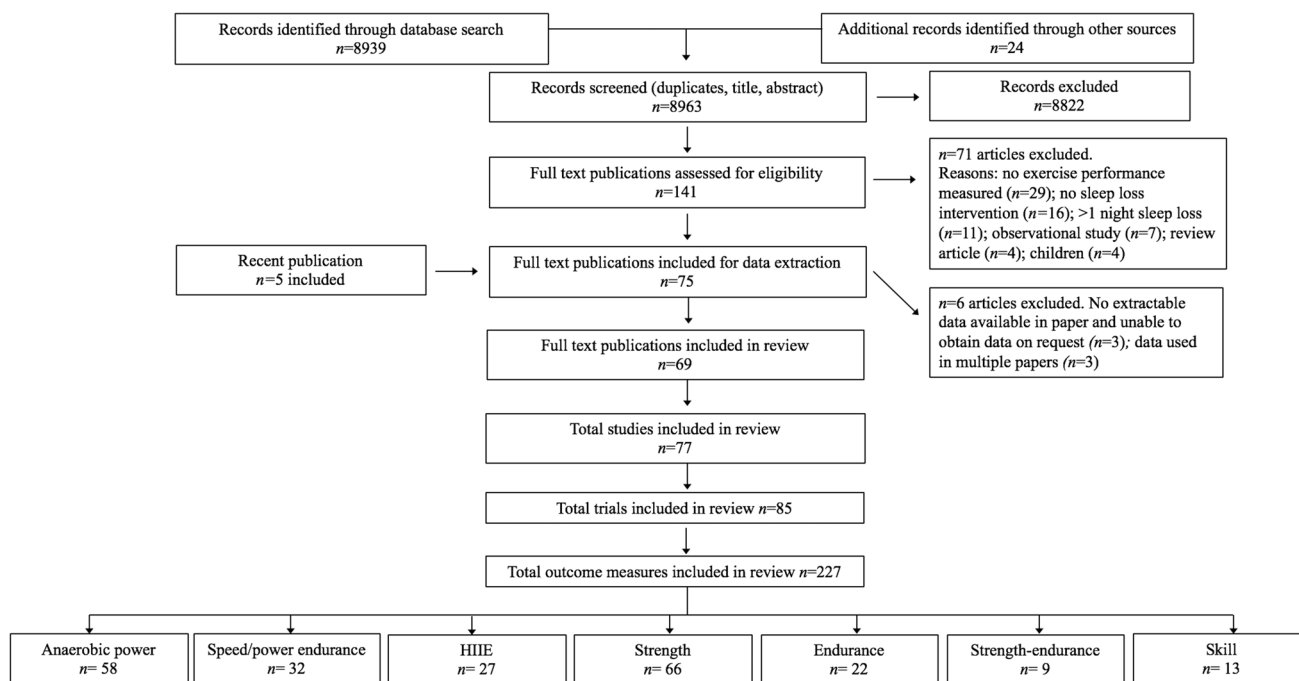
Fig. 2 PRISMA flow chart (study selection methodology). Some publications contained multiple participant pools. In these instances, the individual participant pools were termed 'studies'. Some studies investigated the influence of more than one sleep-loss protocol (i.e., deprivation, early or late restriction). In these instances, the separate study arms were treated as individual investigations, and termed 'tri-als'. Each individual task from a given trial was termed 'outcome measure'. ESM Table S1 provides the original search breakdown; ESM Table S2 provides the origin of included publications; and ESM Table S3 provides the reference and reason for exclusion of full-text publications. *HIIE* high-intensity interval exercise, *ESM* electronic supplementary material

behaviours (e.g., sleep disorder, shift-worker); (6) participants reported recent international travel with experience of jetlag; (7) exercise performance was measured after a period of recovery sleep (sleep latency tests were not considered 'recovery sleep'); and (8) exercise performance data were not adequately reported (i.e., mean ± standard deviation [SD] was not reported or could not be derived).

In the event that data were not adequately reported, the corresponding author was contacted via email in an attempt to retrieve the missing data. Where data were presented in graphical format only, a web-based tool ('WebPlotDigitizer', https://apps.automeris.io/wpd/) was used to extract numeric values.

Several publications identified in the literature search contained more than one intervention and control comparison that was eligible for inclusion. Some publications contained multiple participant pools. In these instances, the individual participant pools were termed 'studies'. Some studies investigated the influence of more than one sleep-loss protocol (a combination of either deprivation, early or late restriction). In these instances, the separate study arms were treated as individual investigations, and termed 'trials'. As single trials sometimes measured serial performance (i.e., multiple times across the trial) and/or used several tasks that generated multiple outcomes, each one could contribute multiple effect

estimates to the review (note, multilevel models were used to account for dependency of effect estimates in statistical analyses [74]; refer to Sect. 2.7 'Statistical Analyses'). In these instances, each individual effect estimate from a given trial was termed an 'outcome measure'.

2.3 Exercise Task Classifications

Each exercise task was reviewed by two investigators (JC and PB) and allocated into one of the following seven categories: anaerobic power, speed/power endurance, high-intensity interval exercise (HIIE), strength, endurance, strength-endurance, and skill. The allocation criteria are defined in Table 1. All discrepancies were resolved in consultation with a third investigator (SS).

Some studies included in this meta-analysis assessed the influence of sleep loss on more than one performance task, either belonging to the same category [40, 41, 53, 58, 59, 63, 64, 75–84], or different categories [41, 43, 44, 56–59, 61, 62, 64, 65, 75, 77–81, 85–102]. For example, Souissi et al. [78] measured anaerobic power in two separate tasks (i.e., squat jump and Wingate test). In these cases, effect estimates were derived for all eligible tasks.

Measures of residual muscular fatigue (i.e., those obtained within minutes of completing an initial performance test)

Table 1 Exercise task categories

Exercise task category	Description of exercise task	Example task
Anaerobic power	Duration ≤ 6 s performed at maximum effort	Wingate (peak power); CMJ; squat jump; 20 m sprint
Speed/power endurance	Maximal continuous exercise—duration > 6 s but < 90 s	30 s Wingate test (mean power); 5 m multiple shuttle test (peak distance); TTE at predetermined workload; repeated CMJ—mean jump height
HIIE	Requires near-maximal effort (~ 45 s) with brief periods of recovery (≤ 4.5 min)	Yo-Yo intermittent recovery test level 1; 5 m multiple shuttle test (total distance)
Endurance	Continuous exercise ≥ 120 s	TTE for incremental exercise test; peak power output at exhaustion during incremental exercise test; 3 km TT
Strength	Maximum force development during a single effort	1RM; MVC (e.g., hand-grip strength test, knee extension)
Strength-endurance	Resistance task ≥ 2 repetitions or > 5 s sustained contraction	Number of repetitions performed at 85% of 1RM; 30 s MVC; knee-extension fatiguing task
Skill	Task that requires high cognitive component for execution	Tennis serving; rugby passing; free-throw shooting (basketball); shooting

HIIE high-intensity interval exercise, *TT* time trial, *RM* repetition maximum, *MVC* maximum voluntary contraction, *TTE* time to exhaustion, *CMJ* counter-movement jump

[64, 89] were not included in the review. However, serial measures were accepted if the preceding test was deemed unlikely to have influenced performance on the subsequent test. For example, if the preceding test used different muscle groups (e.g., knee extensor maximum voluntary contraction (MVC) and knee flexion MVC) [53, 76, 82, 83] or a contralateral muscle group [82], or if the same test was repeated at separate times of the day (e.g., once at 0600 h, then at 1700 h) [43, 53, 62, 64, 79–81, 90], then each measurement was included and considered as a separate 'outcome measure'.

2.4 Primary and Secondary Research Outcomes

The primary outcome in this investigation was the percentage change in exercise performance ($\%_\Delta EP$) following sleep loss (i.e., sleep restriction or sleep deprivation), calculated using the following formula:

$$\%_\Delta EP = \frac{(EP\ sleep\ loss - EP\ normal\ sleep)}{EP\ normal\ sleep} \times 100,$$

where 'EP sleep loss' was exercise performance measured following sleep loss and 'EP normal' was exercise performance measured under control conditions.

2.5 Data Extraction

Data were extracted in accordance with the Cochrane Handbook for Systematic Reviews of Interventions Checklist of Items to Consider in Data Collection or Data Extraction [103] and entered into a Microsoft Excel spreadsheet (Microsoft Corporation, Redmond, WA, USA). Extracted data included (1) participant characteristics (e.g., training

status, age, body mass, sex, aerobic power [$\dot{V}O_{2peak}$]); (2) pretrial standardisation procedures; (3) the sleep-loss protocol (e.g., deprivation, restriction); (4) sleep location (e.g., laboratory, home); (5) the instrument used to monitor and record hours slept; (6) protocol used to assess exercise performance; (7) timing of tests relative to the sleep/wake cycle; and (8) whether or not participants were fed/fasted prior to performance testing.

2.6 Quality Assessment

The included publications were assessed based on their methodological quality using the Rosendal Scale (see Table 2 in the article by van Rosendal et al. [104]). This scale, which combines the Jadad scoring system [105], PEDro scale [106] and Delphi List [107], assesses a number of factors associated with the minimisation of experimental bias (e.g., blinding, participant selection, randomisation, data reporting). Excellent methodological quality is indicated by a Rosendal score ≥ 60% [105]. Scoring was determined by dividing the number of 'yes' responses by the total number of applicable items. Scores were compared between two investigators (JC and CI) conducting the assessments and any discrepancies were resolved (with a third investigator consulted [DM] if agreement could not be reached). As such, the final score is an agreed rating for each publication.

2.7 Statistical Analyses

A series of multilevel meta-analyses and meta-regression analyses were performed using R Studio (version 4.0.1) with the metafor-package [108] and syntax adapted from Assink and Wibbelink [74]. A two-level meta-analysis is

Table 2 Meta-analysis results for effect of sleep loss on exercise performance

Exercise category	Outcomes, n	Exercise performance percentage change		Heterogeneity	
		Mean (95% CI)	p value	I^2 value	p value
All categories					
Overall	227	−7.56 (−11.9 to −3.13)	0.001	98.1	<0.001
Sleep-loss condition					
Deprivation	97	−5.25 (−8.01 to −2.48)	<0.001	96.5	<0.001
Restriction	130	−8.59 (−13.6 to −3.61)	0.001	98.3	<0.001
Early restriction	62	−5.85 (−13.4 to 1.66)	0.125	93.5	<0.001
Late restriction	60	−7.39 (−10.1 to −4.66)	<0.001	98.3	<0.001
Anaerobic power					
Overall	58	−6.26 (−9.10 to −3.41)	<0.001	98.1	<0.001
Sleep-loss condition					
Deprivation	25	−6.39 (−11.7 to −1.09)	0.020	99.2	<0.001
Restriction	33	−5.99 (−9.22 to −2.77)	0.001	94.1	<0.001
Early restriction	11	−0.50 (−2.00 to 1.00)	0.477	0.04	0.770
Late restriction	22	−7.47 (−11.1 to −3.85)	<0.001	95.4	<0.001
Speed/power endurance					
Overall	32	−2.90 (−4.97 to −0.82)	0.008	96.3	<0.001
Sleep-loss condition					
Deprivation	12	−2.93 (−8.05 to 2.18)	0.233	91.1	<0.001
Restriction	20	−3.23 (−5.94 to −0.53)	0.022	96.4	<0.001
Early restriction	7	0.49 (−2.05 to 3.04)	0.652	24.4	0.366
Late restriction	13	−4.38 (−7.15 to −1.62)	0.005	97.3	<0.001
HIIE					
Overall	27	−6.15 (−10.5 to −1.77)	0.008	98.9	<0.001
Sleep-loss condition					
Deprivation	9	−2.38 (−12.1 to 7.32)	0.587	99.0	<0.001
Restriction	18	−8.77 (−13.3 to −4.27)	0.001	98.3	<0.001
Early restriction	8	−3.15 (−9.68 to 3.37)	0.291	73.2	0.001
Late restriction	10[a]	−11.5 (−16.3 to −6.71)	<0.001	99.2	<0.001
Strength					
Overall	66	−2.85 (−4.47 to −1.23)	<0.001	62.2	<0.001
Sleep-loss condition					
Deprivation	29	−3.00 (−4.52 to −1.48)	<0.001	49.2	<0.001
Restriction	37	−2.77 (−6.75 to 1.21)	0.167	74.9	<0.001
Early restriction	26	−1.16 (−2.57 to 0.25)	0.102	0.02	0.952
Late restriction	11	−4.45 (−9.30 to 0.41)	0.068	83.7	<0.001
Endurance					
Overall	22	−5.55 (−8.12 to −2.99)	<0.001	86.5	<0.001
Sleep-loss condition					
Deprivation	14[a]	−6.75 (−10.3 to −3.25)	<0.001	91.2	<0.001
Restriction	8	−3.27 (−5.06 to −1.47)	0.004	<0.001	0.914
Early restriction	2[a]	−5.28 (−9.17 to −1.39)	0.008	0.00	0.798
Late restriction	3[a]	−3.72 (−6.96 to −0.47)	0.025	<0.001	0.620
Strength-endurance					
Overall	9	−9.85 (−19.6 to −0.13)	0.048	85.4	<0.001
Deprivation	6	−6.06 (−14.9 to 2.80)	0.139	45.6	0.255
Restriction	3	−18.3 (−35.6 to −0.96)	0.045	88.3	0.001
Skill					
Overall	13	−20.9 (−27.0 to −14.9)	<0.001	94.1	<0.001

Table 2 (continued)

Exercise category	Outcomes, n	Exercise performance percentage change		Heterogeneity	
		Mean (95% CI)	p value	I^2 value	p value
Sleep-loss condition					
Deprivation	2[a]	− 20.9 (− 23.6 to − 18.2)	< 0.001	0.00	0.342
Restriction	11	− 21.0 (− 29.1 to − 12.9)	< 0.001	95.4	< 0.001
Early restriction	8	− 23.9 (− 33.6 to − 14.2)	< 0.001	94.8	< 0.001
Late restriction	1				

A negative effect estimate indicates a decrease in performance under the intervention condition ('sleep loss')

Deprivation: participants did not sleep for an extended period of time (i.e., whole night); restriction: total sleep time ≤ 6 h in any 24 h period—this category is a combination of early restriction, late restriction, fragmented sleep and non-specified sleep restriction protocols; early restriction: participants delayed sleep (i.e., went to sleep at a later time); late restriction; participants awakened earlier than normal

HIIE high-intensity interval exercise, *CI* confidence interval

[a]All outcomes were from independent studies and the meta-analysis was run without dependency levels (i.e., simple meta-analysis)

equivalent to a traditional random-effects analysis in which there is only one random effect. For the meta-analysis and meta-regression analysis when all seven exercise categories were combined, we added random effects at two additional levels to account for dependency among effect estimates derived from the (1) same studies; and (2) same exercise categories. Therefore, the four sources of variance modelled were: (Level 1) the sampling variance for the observed effect estimates; (Level 2) the variance between effect estimates derived from the same studies; (Level 3) the variance between effect estimates derived from the same exercise categories; and (Level 4) the variance between studies. The subgroup analyses (described in Sect. 2.7.1) accounted for dependency among effect estimates derived from the same studies only. An example of the accompanying R script (for the combined exercise category analysis) is available in electronic supplementary material [ESM] Appendix S1.

Individual effect estimates were calculated as the $\%_\Delta$ EP (as described in Sect. 2.4), where a negative effect estimate indicates a decrease in exercise performance under the intervention condition ('sleep loss'). As the current review used the $\%_\Delta$ EP (i.e., rather than the net difference), the SD of exercise performance change could not be determined via standard methods. Instead, t statistics (or p values) derived from paired t tests were used to calculate the SD of the percentage change in exercise performance (SD_Δ). Where an exact value was quoted [45, 76, 88, 92, 109–111], the calculation was performed using the following formula [112]:

$$SD_\Delta = \frac{|\%_\Delta EP|}{t \text{ statistic}} \times \sqrt{n} \tag{1}$$

where SD_Δ is the SD of the percentage change in exercise performance and n is the number of participants. Where only $p > x$ or $p < 0.05$ was reported (and raw exercise performance data could not be retrieved), the missing t-statistic was imputed using the following formula:

$$SD_\Delta = \sqrt{\left(SD^2_{\text{sleep loss EP}} + SD^2_{\text{normal sleep EP}}\right) - \left(2 \times R \times SD_{\text{sleep loss EP}} \times SD_{\text{normal sleep EP}}\right)}, \tag{2}$$

2.7.1 Weighted Mean Effect

Meta-analyses were performed to determine the influence of sleep loss (vs. control) on overall exercise performance (all exercise categories combined) and each respective exercise category (i.e., anaerobic power, speed/power endurance, HIIE, strength, endurance, strength-endurance, skill).

where SD_Δ is the SD of the net exercise performance change and R is the correlation coefficient. R was approximated (0.71) as the mean correlation coefficient calculated using raw exercise performance data from nine outcome measurements derived from seven publications [45, 76, 88, 92, 109–111], as indicated by Higgins and Green [112]. Sensitivity analyses were performed using R = 0.30 and 0.80 to

test the robustness of the analysis to the imputed value. In addition, outcome measures were individually excluded (i.e., one-out method) to examine their influence on the weighted mean effect estimate. The imputed SD_Δ (net change) used to derive the t-statistic was calculated using the following formula:

$$t\text{ - statistic} = \frac{\text{mean EP}_{\text{sleep loss}} - \text{mean EP}_{\text{normal sleep}}}{\left(SD_\Delta \div \sqrt{n}\right)}. \quad (3)$$

Effect estimates were weighted by the inverse variance of the performance change and statistical significance was attained if the 95% confidence interval (CI) did not include zero. Heterogeneity was assessed using Cochran's Q, the I^2 index and the within- and between-cluster variance components (i.e., σ^2). Significant heterogeneity was indicated by a p value < 0.05 for Cochran's Q [113]. Subgroup analyses were performed to investigate the influence of (1) the sleep-loss protocol implemented (e.g., sleep deprivation, sleep restriction [i.e., the combination of early and late restriction, fragmented sleep and non-specified sleep restriction protocols]), and early and late restriction; (2) the timing of exercise following sleep loss (ante meridiem [AM] vs. post meridiem [PM]); and (3) body limb strength (upper- vs. lower-body strength), on $\%_\Delta EP$. The time that body limb strength tasks were conducted following sleep loss and its impact on $\%_\Delta EP$ were also explored for each sleep-loss protocol implemented.

2.7.2 Meta-Regression Analysis

Restricted maximum likelihood (REML) multilevel simple meta-regression analyses were performed to determine whether the $\%_\Delta EP$ between treatments was influenced by the time awake prior to the exercise task (i.e., the number of hours from their last waking to the start of the exercise task). Regression analyses were examined for influential cases and outliers (i.e., studentised residuals, Cook's distance and centred leverage values). Statistical significance was accepted as $p < 0.05$.

3 Results

3.1 Overview of the Included Studies and Study Quality

Seventy-five publications met the inclusion criteria; however six had to be excluded because data (1) could not be extracted (or retrieved) [114–116]; or (2) were reported in another included publication [117–119]. Therefore, 69 publications remained for analysis. These publications provided

77 individual 'studies' (i.e., eight additional participant pools [82, 90, 120–123]). Ten studies investigated the influence of more than one sleep-loss protocol (a combination of either deprivation, early or late restriction) [44, 57, 64–67, 81, 87, 124, 125]. This resulted in 85 trials, in which 14 measured the same exercise task(s) multiple times (twice, e.g., once at 0600 h, then at 1800 h [43, 53, 62, 64, 79–81, 90] or more than two times [45, 54, 55]). Thirty-six trials (derived from 23 studies) reported only one outcome measure [45, 49, 50, 54, 55, 66, 67, 110, 111, 116, 120–132], with the remaining trials yielding multiple outcome measures. This resulted in 227 separate outcome measures being included in the overall analysis. These outcome measures were further classified into their respective exercise categories (anaerobic power: $n = 58$; speed/power endurance: $n = 32$; HIIE: $n = 27$; strength: $n = 66$; endurance: $n = 22$; strength-endurance: $n = 9$; skill: $n = 13$). The location of the sleep protocol (i.e., slept in the laboratory or at home) and the method used to monitor sleep parameters (i.e., duration/quality) for each outcome measure are provided in ESM Table S4. Participant characteristics, mode of exercise, and timing of the exercise task are outlined in ESM Table S5; an overview of each included study is provided in ESM Appendix S2. Methodological quality assessment yielded an average Rosendal score of $67 \pm 9\%$, with all but one publication [83] scoring $\geq 50\%$. Results of the quality assessment are shown in ESM Table S6.

3.2 Overall Exercise Performance (All Exercise Categories)

Seventy-seven studies ($n = 959$; 89% male), providing 227 outcome measures, were included in this analysis. The overall weighted mean effect estimate (Table 2) indicated a negative influence of sleep loss on exercise performance (mean $\%_\Delta = -7.56\%$, 95% CI -11.9 to -3.13, $p = 0.001$, $I^2 = 98.1\%$) [ESM Fig. S1]. The magnitude and significance of this effect was stable during one-out ($\%_\Delta EP$ range $= -7.91$ to -7.28% and 95% CIs did not include zero) and sensitivity analyses (ESM Table S7).

Subgroup analyses demonstrated that exercise performance was negatively affected by sleep deprivation, sleep restriction and late restriction, but not early restriction (Table 2). Results indicated that sleep loss had a consistent negative influence on performance when tasks were performed in both the AM and PM; however, the magnitude of the effect was larger for PM (Table 3).

Meta-regression analyses (Fig. 3 and Table 4) identified significant relationships between time awake prior to completing the exercise task and $\%_\Delta EP$ for sleep restriction (mean $\%_\Delta = -0.36$, 95% CI -0.52 to -0.19, $p < 0.001$), and late restriction (mean $\%_\Delta = -0.55$, 95% CI -0.82 to -0.28, $p < 0.001$), but not sleep deprivation (mean $\%_\Delta = -0.30$,

Table 3 Meta-analysis results for the effect of sleep loss on exercise tasks performed in the AM or PM

Exercise category	Outcomes, n	Exercise performance percentage change		Heterogeneity	
		Mean (95% CI)	p value	I^2 value	p value
All categories					
AM vs. PM					
Overall (exercise AM)	115	−5.42 (−9.66 to −1.17)	0.013	93.5	<0.001
Overall (exercise PM)	106	−8.31 (−13.2 to −3.37)	0.001	98.9	<0.001
Sleep-loss condition					
Deprivation (exercise AM)	59	−3.48 (−5.89 to −1.08)	0.005	94.2	<0.001
Deprivation (exercise PM)	35	−6.85 (−11.3 to −2.39)	0.004	97.5	<0.001
Restriction (exercise AM)	56	−5.96 (−11.5 to −0.43)	0.035	90.7	<0.001
Restriction (exercise PM)	71	−9.50 (−14.9 to −4.12)	0.001	99.0	<0.001
Early restriction (exercise AM)	27	−1.55 (−4.66 to 1.56)	0.315	55.1	0.437
Early restriction (exercise PM)	35	−6.23 (−13.9 to 1.44)	0.108	94.7	<0.001
Late restriction (exercise AM)	23	−2.48 (−4.36 to −0.60)	0.012	46.1	0.048
Late restriction (exercise PM)	34	−9.67 (−13.1 to −6.24)	<0.001	99.1	<0.001
Anaerobic power					
AM vs. PM					
Overall (exercise AM)	27	−4.58 (−9.14 to −0.24)	0.049	97.0	<0.001
Overall (exercise PM)	30	−7.37 (−10.3 to −4.40)	<0.001	97.8	<0.001
Sleep-loss condition					
Deprivation (exercise AM)	14	−6.38 (−14.5 to 1.73)	0.113	98.5	<0.001
Deprivation (exercise PM)	11	−5.49 (−7.93 to −3.04)	<0.001	93.5	<0.001
Restriction (exercise AM)	13	−2.77 (−5.77 to 0.23)	0.067	72.3	0.010
Restriction (exercise PM)	19	−8.35 (−13.1 to −3.56)	0.002	96.0	<0.001
Early restriction (exercise AM)	5	0.25 (−2.55 to 3.05)	0.817	<0.01	0.988
Early restriction (exercise PM)	6	−1.10 (−3.42 to 1.23)	0.280	0.05	0.391
Late restriction (exercise AM)	8	−3.46 (−7.22 to 0.31)	0.067	78.1	0.002
Late restriction (exercise PM)	13	−10.1 (−14.9 to −5.13)	0.001	96.3	<0.001
Speed/power endurance					
AM vs. PM					
Overall (exercise AM)	14	0.11 (−0.94 to 1.16)	0.823	<0.001	0.721
Overall (exercise PM)	15	−6.78 (−10.8 to −2.80)	0.003	98.5	<0.001
Sleep-loss condition					
Deprivation (exercise AM)	5[a]	0.90 (−0.89 to 2.69)	0.323	14.0	0.203
Deprivation (exercise PM)	5[a]	−7.11 (−14.4 to 0.20)	0.057	93.9	<0.001
Restriction (exercise AM)	9	−0.36 (−1.84 to 1.12)	0.588	<0.001	0.964
Restriction (exercise PM)	10	−5.58 (−10.4 to −0.76)	0.028	98.8	<0.001
Early restriction (exercise AM)	4[a]	0.62 (−1.55 to 2.79)	0.575	0.00	0.902

Table 3 (continued)

Exercise category	Outcomes, n	Exercise performance percentage change		Heterogeneity	
		Mean (95% CI)	p value	I² value	p value
Early restriction (exercise PM)	3ᵃ	0.43 (−3.51 to 4.37)	0.832	68.3	0.056
Late restriction (exercise AM)	5ᵃ	−0.86 (−2.40 to 0.68)	0.275	0.00	0.954
Late restriction (exercise PM)	7ᵃ	−7.17 (−10.7 to −3.66)	<0.001	98.5	<0.001
HIIE					
AM vs. PM					
Overall (exercise AM)	11	−1.51 (−10.4 to 7.42)	0.714	97.7	<0.001
Overall (exercise PM)	16	−8.34 (−12.2 to −4.47)	0.001	98.5	<0.001
Sleep-loss condition					
Deprivation (exercise AM)	5ᵃ	−2.06 (−14.1 to 10.0)	0.737	99.3	<0.001
Deprivation (exercise PM)	4ᵃ	−4.13 (−6.50 to −1.76)	<0.001	81.2	0.013
Restriction (exercise AM)	6	−3.39 (−13.3 to 6.55)	0.421	66.5	0.074
Restriction (exercise PM)	12	−10.2 (−15.4 to −4.97)	0.001	99.0	<0.001
Early restriction (exercise AM)	5	−1.10 (−10.7 to 8.53)	0.767	57.2	0.176
Early restriction (exercise PM)	3ᵃ	−4.79 (−13.6 to 3.98)	0.284	83.6	<0.001
Late restriction (exercise AM)	1				
Late restriction (exercise PM)	9ᵃ	−11.5 (−16.7 to −6.24)	<0.001	99.4	<0.001
Strength					
AM vs. PM					
Overall (exercise AM)	39	−1.78 (−3.22 to −0.33)	0.017	17.6	0.570
Overall (exercise PM)	26	−4.58 (−7.59 to −1.58)	0.004	79.5	<0.001
Sleep-loss condition					
Deprivation (exercise AM)	21	−2.43 (−4.47 to −0.38)	0.022	31.8	0.115
Deprivation (exercise PM)	8	−3.79 (−7.27 to −0.32)	0.037	71.5	<0.001
Restriction (exercise AM)	18	−0.43 (−2.41 to 1.54)	0.650	<0.001	0.999
Restriction (exercise PM)	18	−5.20 (−11.0 to 0.59)	0.075	82.3	<0.001
Early restriction (exercise AM)	12	−0.55 (−3.21 to 2.11)	0.659	<0.001	0.985
Early restriction (exercise PM)	14	−1.51 (−4.41 to 1.39)	0.281	27.1	0.631
Late restriction (exercise AM)	6	−0.26 (−4.06 to 3.54)	0.867	<0.001	0.989
Late restriction (exercise PM)	4	−10.5 (−20.6 to −0.39)	0.046	84.0	<0.001
Endurance					
AM vs. PM					
Overall (exercise AM)	12	−6.50 (−11.1 to −1.86)	0.010	88.6	<0.001
Overall (exercise PM)	9	−3.56 (−4.67 to −2.45)	<0.001	<0.001	0.976
Sleep-loss condition					
Deprivation (exercise AM)	9ᵃ	−7.83 (−12.9 to −2.72)	0.003	88.5	<0.001

Table 3 (continued)

Exercise category	Outcomes, n	Exercise performance percentage change		Heterogeneity	
		Mean (95% CI)	p value	I^2 value	p value
Deprivation (exercise PM)	4[a]	−3.45 (−4.48 to −2.42)	<0.001	0.00	0.905
Restriction (exercise AM)	3[a]	−2.67 (−4.62 to −0.73)	0.007	0.00	0.794
Restriction (exercise PM)	5	−4.11 (−7.40 to −0.82)	0.026	<0.001	0.855
Early restriction (exercise AM)	0				
Early restriction (exercise PM)	2[a]	−5.28 (−9.17 to −1.39)	0.008	0.00	0.798
Late restriction (exercise AM)	2[a]	−2.92 (−6.83 to 0.98)	0.143	0.00	0.507
Late restriction (exercise PM)	0				
Strength-endurance					
AM vs. PM					
Overall (exercise AM)	8	−11.2 (−23.3 to 0.85)	0.064	87.0	<0.001
Overall (exercise PM)	1				
Sleep-loss condition					
Deprivation (exercise AM)	5	−7.06 (−22.9 to 8.82)	0.285	60.5	0.172
Deprivation (exercise PM)	1				
Restriction (exercise AM)	3	−18.3 (−35.6 to −0.96)	0.045	88.3	0.001
Restriction (exercise PM)	0				
Skill					
AM vs. PM					
Overall (exercise AM)	4	−14.2 (−26.7 to −1.68)	0.037	87.0	<0.001
Overall (exercise PM)	9	−22.9 (−29.7 to −16.0)	<0.001	93.8	<0.001
Sleep-loss condition					
Deprivation (exercise AM)	0				
Deprivation (exercise PM)	2[a]	−20.9 (−23.6 to −18.2)	<0.001	0.00	0.342
Restriction (exercise AM)	4	−14.2 (−26.7 to −1.67)	0.037	87.0	<0.001
Restriction (exercise PM)	7	−23.7 (−34.0 to −13.4)	0.001	95.5	<0.001
Early restriction (exercise AM)	1				
Early restriction (exercise PM)	7	−23.7 (−34.0 to −13.4)	0.001	95.5	<0.001
Late restriction (exercise AM)	1				
Late restriction (exercise PM)	0				

A negative effect estimate indicates a decrease in performance under the intervention condition ('sleep loss')

Deprivation: participants did not sleep for an extended period of time (i.e., whole night); restriction: total sleep time ≤6 h in any 24 h period – this category is a combination of early restriction, late restriction, fragmented sleep and sleep restriction protocols not specified; early restriction: participants delayed sleep (i.e., went to sleep at a later time); late restriction; participants awakened earlier than normal

HIIE high-intensity interval exercise, *AM* ante meridiem, *PM* post meridiem, *CI* confidence interval

[a] All outcomes were from independent studies and the meta-analysis was run without dependency levels (i.e., simple meta-analysis)

95% CI -0.59 to 0.01, $p = 0.051$), early restriction (mean $\%_\Delta = -0.10$, 95% CI -0.27 to 0.09, $p = 0.323$) or when all sleep protocols were combined (mean $\%_\Delta = -0.09$, 95% CI -0.19 to 0.01, $p = 0.095$). However, it is important to note that for sleep deprivation, an outcome measure from Arazi et al. [85] was identified as an influential outlier (based on Cook's distance). When performing one-out analysis, removal of this outcome measure yielded a significant result (mean $\%_\Delta = -0.27$, 95% CI -0.48 to -0.05, $p = 0.015$).

3.3 Anaerobic Power

Thirty-two studies ($n = 368$; 92% male), providing 58 outcome measures, were included in this analysis. The overall weighted mean effect estimate (Table 2) indicated a negative influence of sleep loss on anaerobic power (mean $\%_\Delta = -6.26\%$, 95% CI -9.10 to -3.41, $p < 0.001$, $I^2 = 98.1\%$) [ESM Fig. S2]. The magnitude and statistical significance of the effect were stable during one-out (mean $\%_\Delta$ range $= -6.59$ to -5.24% and 95% CIs did not include zero) and sensitivity analyses (ESM Table S8).

Subgroup analyses showed that anaerobic power was negatively affected by sleep deprivation, sleep restriction and late restriction, but not early restriction (Table 2). Results were consistent for anaerobic power tasks performed in the PM, while performance in the AM tended to be unaffected, with the exception of analysis for all sleep-loss protocols combined (Table 3).

Meta-regression analyses identified significant relationships between time awake prior to completing the exercise task and $\%_\Delta$ in anaerobic power when all sleep-loss protocols were included (mean $\%_\Delta = -0.20$, 95% CI -0.37 to -0.04, $p = 0.016$), when both sleep restriction protocols (i.e., early and late restriction) were combined (mean $\%_\Delta = -0.47$, 95% CI -0.79 to -0.14, $p = 0.007$) and late restriction (mean $\%_\Delta = -0.56$, 95% CI -1.09 to -0.02, $p = 0.043$). No significant relationships were detected for the other sleep-loss protocols (Table 4).

3.4 Speed/Power Endurance

Twenty studies ($n = 261$; 97% male), providing 32 outcome measures, were included in this analysis. The overall weighted mean effect estimate (Table 2) indicated a negative influence of sleep loss on speed/power endurance (mean $\%_\Delta = -2.90\%$, 95% CI -4.97 to -0.82, $p = 0.008$, $I^2 = 96.3\%$) [ESM Fig. S3]. The magnitude and significance of the effect were stable during one-out (mean $\%_\Delta$ range $= -3.72$ to -2.43% and 95% CIs did not include zero) and sensitivity analyses (ESM Table S9).

Subgroup analyses showed that speed/power endurance was negatively affected by sleep restriction and late-restriction protocols, but not sleep deprivation or early restriction

(Table 2). However, when the trial from Abedelmalek et al. [62] was removed (during one-out analyses), the effect on sleep restriction was no longer significant (ESM Table S9). Results indicated that sleep loss had a consistent negative influence on speed/power endurance when analysis was isolated to tasks performed in the PM, while tasks performed in the AM were unaffected.

Meta-regression analyses (Table 4) detected significant relationships between time awake prior to completing the exercise task and the $\%_\Delta$ in speed/power endurance following sleep deprivation (mean $\%_\Delta = -1.00$, 95% CI -1.80 to -0.21, $p = 0.018$), sleep restriction (mean $\%_\Delta = -0.46$, 95% CI -0.71 to -0.22, $p < 0.001$) and late restriction (mean $\%_\Delta = -0.57$, 95% CI -0.98 to -0.15, $p = 0.012$). No significant relationships were detected for the other sleep-loss protocols (Table 4).

3.5 High-Intensity Interval Exercise

Eighteen studies ($n = 207$; 88% male), providing 27 outcome measures, were included in this analysis. The overall weighted mean effect estimate (Table 2) indicated a negative influence of sleep loss on HIIE (mean $\%_\Delta = -6.15\%$, 95% CI -10.5 to -1.77, $p = 0.008$, $I^2 = 98.9\%$) [ESM Fig. S4]. The magnitude and statistical significance of the effect were stable during one-out (mean $\%_\Delta$ range $= -7.54$ to -5.57% and 95% CIs did not include zero) and sensitivity analyses (ESM Table S10).

Subgroup analyses indicated that HIIE performance was negatively affected following sleep restriction and late restriction, but not sleep deprivation or early restriction (Table 2). However, when the study by Arazi et al. [85] was removed (during one-out analyses) the effect for sleep deprivation was significant (mean $\%_\Delta = -4.21\%$, 95% CI -6.45 to -1.97, $p = 0.003$). Results indicated that sleep loss had a consistent negative influence on HIIE when analysis was conducted on tasks performed in the PM (except for early restriction), while tasks performed in the AM were unaffected.

No significant relationships between time awake prior to completing the task and $\%_\Delta$ in HIIE were identified for meta-regression analysis with any of the sleep-loss protocols (Table 4).

3.6 Strength

Twenty-five studies ($n = 289$; 74% male), providing 66 outcome measures, were included in this analysis. The overall weighted mean effect estimate (Table 2) indicated a negative influence of sleep loss on strength (mean $\%_\Delta = -2.85\%$, 95% CI -4.47 to -1.23, $p < 0.001$, $I^2 = 62.2\%$) [ESM Fig. S5]. The magnitude and statistical significance of the effect were stable during one-out (mean $\%_\Delta$ range $= -3.20$ to -2.27%
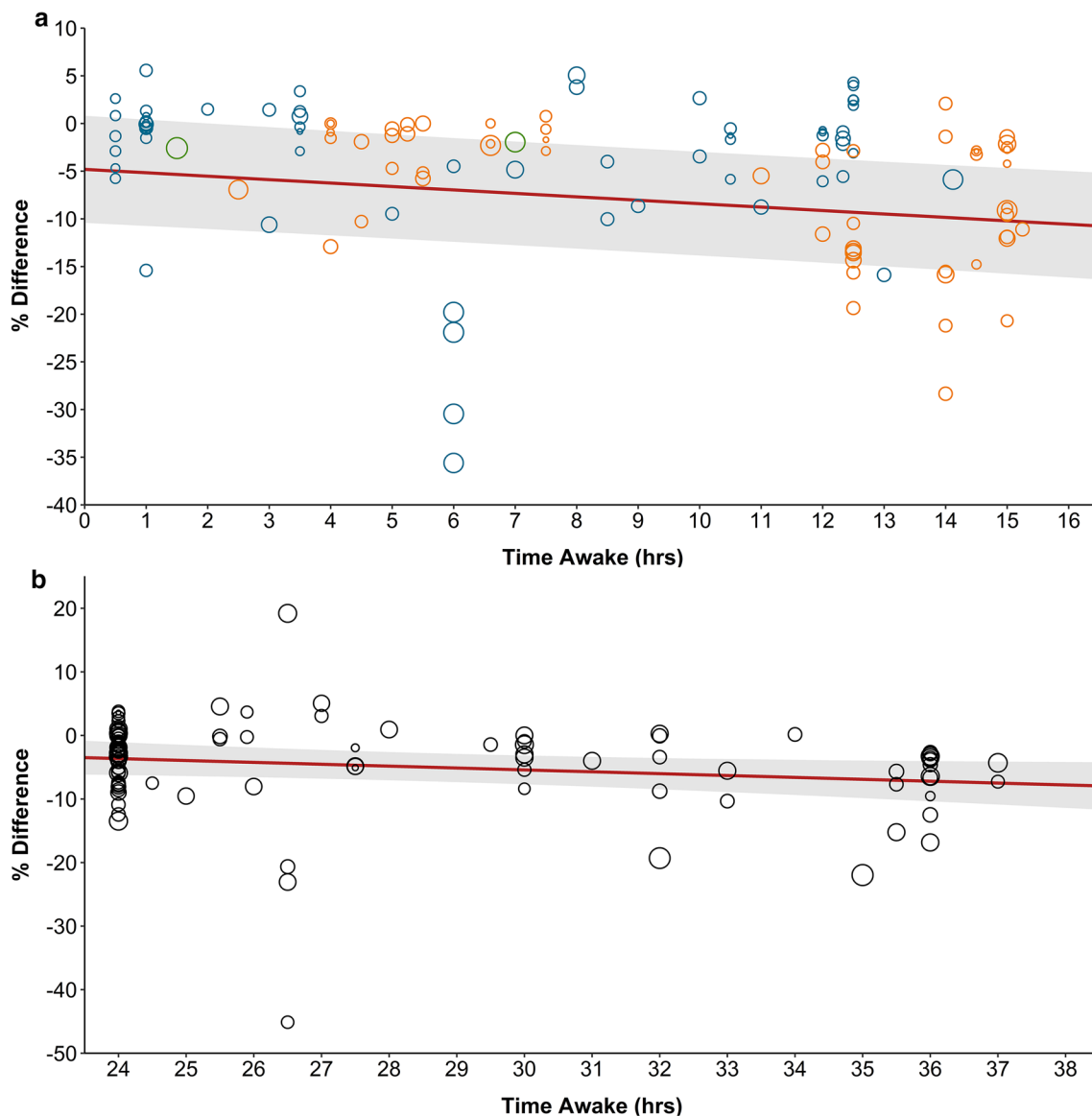
Fig. 3 Relationship between time awake and the mean percentage change (95% CIs shown by the grey shaded area) in exercise performance for all tasks (combined exercise categories). Circle diameter corresponds to the weight of the outcome measure from each trial. **a** Sleep restriction ($n=121$): mean $\%_\Delta = -0.36$, 95% CI -0.52 to -0.19; $p<0.001$. Green circles represent 'sleep restriction' (not further defined); blue circles represent 'early restriction'; and orange circles represent 'late restriction'. **b** Sleep deprivation ($n=97$): mean $\%_\Delta = -0.30$, 95% CI -0.59 to 0.01; $p=0.051$. Deprivation: participants did not sleep for an extended period of time (i.e., whole night); early restriction: participants delayed sleep (i.e., went to sleep at a later time); late restriction: participants awakened earlier than normal. *CIs* confidence intervals

and 95% CIs did not include zero) and sensitivity analyses (ESM Table S11).

In subgroup analyses, a significant negative influence was only observed for sleep deprivation (mean $\%_\Delta = -3.00\%$, 95% CI -4.52 to -1.48, $p<0.001$, $I^2=49.2\%$) (Table 2). Results indicated that sleep loss had a consistent negative influence on strength when analysis was isolated to tasks performed in the PM, while tasks performed in the AM were generally unaffected (Table 3).

The effects of sleep loss were also conditional on body–limb categorisation, with tasks involving lower-body strength demonstrating a negative influence on performance, while tasks requiring upper-body strength were unaffected (Table 5; limb strength AM vs. PM comparison in ESM Table S12).

Meta-regression analyses (Table 4) detected a significant relationship between time awake prior to completing the exercise task and $\%_\Delta$ in strength, but only following late restriction (mean $\%_\Delta = -1.07$, 95% CI -2.05 to -0.10,

Table 4 Meta-regression relationship between time awake and percentage change in exercise performance

Exercise category	Sleep-loss condition	Outcomes, *n*	Exercise performance percentage change	
			Coefficient (95% CI)	*P* value
All categories	Overall	218	−0.09 (−0.19 to 0.01)	0.095
	Deprivation	97	−0.30 (−0.59 to 0.01)	0.051
	Restriction	121	−0.36 (−0.52 to −0.19)	<0.001
	Early restriction	62	−0.10 (−0.27 to 0.09)	0.323
	Late restriction	57	−0.55 (−0.82 to −0.28)	<0.001
Anaerobic power	Overall	57	−0.20 (−0.37 to −0.04)	0.016
	Deprivation	25	−0.19 (−0.49 to 0.12)	0.213
	Restriction	32	−0.47 (−0.79 to −0.14)	0.007
	Early restriction	11	0.16 (−0.47 to 0.15)	0.266
	Late restriction	21	−0.56 (−1.09 to −0.02)	0.043
Speed/power endurance	Overall	31	−0.19 (−0.39 to 0.01)	0.063
	Deprivation	12	−1.00 (−1.80 to −0.21)	0.018
	Restriction	19	−0.46 (−0.71 to −0.22)	<0.001
	Early restriction	7	−0.18 (−0.62 to 0.26)	0.344
	Late restriction	12	−0.57 (−0.98 to −0.15)	0.012
HIIE	Overall	27	−0.05 (−0.21 to 0.11)	0.532
	Deprivation	9	−0.05 (−0.26 to 0.16)	0.605
	Restriction	18	−0.79 (−1.59 to 0.02)	0.056
	Early restriction	8	−0.41 (−2.14 to 1.32)	0.586
	Late restriction	10	0.59 (−1.56 to 2.74)	0.546
Strength	Overall	65	−0.08 (−0.23 to 0.07)	0.315
	Deprivation	29	−0.11 (−0.46 to 0.25)	0.538
	Restriction	36	−0.23 (−0.52 to 0.05)	0.108
	Early restriction	26	−0.04 (−0.33 to 0.25)	0.792
	Late restriction	10	−1.07 (−2.05 to −0.10)	0.035
Endurance	Overall	21	−0.12 (−0.39 to 0.14)	0.345
	Deprivation	14	0.77 (−0.55 to 2.09)	0.253
	Restriction	7	−0.24 (−0.77 to 0.29)	0.290
	Early restriction	2		
	Late restriction	3	−0.46 (−1.97 to 1.05)	0.548
Skill	Overall	11	−0.03 (−0.57 to 0.51)	0.896
	Sleep deprivation	2		
	Restriction	9	−0.15 (−1.39 to 1.09)	0.782
	Early restriction	8	−0.02 (−1.28 to 1.25)	0.975
	Late restriction	1		

Deprivation: participants did not sleep for an extended period of time (i.e., whole night); restriction: total sleep time ≤6 h in any 24 h period—this category is a combination of early restriction, late restriction, fragmented sleep and sleep restriction protocols not specified; early restriction: participants delayed sleep (i.e., went to sleep at a later time); late restriction; participants awakened earlier than normal

HIIE high-intensity interval exercise, *CI* confidence interval

$p = 0.035$). No significant relationships were detected for the other sleep-loss protocols (Table 4).

3.7 Endurance

Twenty studies ($n = 237$; 91% male), providing 22 outcome measures, were included in this analysis. The overall weighted mean effect estimate (Table 2) indicated a negative influence of sleep loss on endurance (mean $\%_\Delta = -5.55\%$, 95% CI −8.12 to −2.99, $p < 0.001$, $I^2 = 86.5\%$) [ESM Fig. S6]. The magnitude and statistical significance of the effect were stable during one-out (mean $\%_\Delta$ range = −5.94 to −3.72% and 95% CIs did not include zero) and sensitivity analyses (ESM Table S13).

Subgroup analyses showed that all sleep protocols were negatively affected by sleep loss (Table 2); however, there

Table 5 Influence of sleep loss on body–limb strength

Exercise category	Outcomes, n	Exercise performance percentage change		Heterogeneity	
		Mean (95% CI)	p value	I^2 value	p value
Upper- vs. lower-body strength					
Overall upper body	18	-1.63 (-3.30 to 0.04)	0.056	32.7	0.069
Overall lower body	46	-3.42 (-5.54 to -1.31)	0.002	65.6	< 0.001
Sleep-loss condition					
Upper body					
Deprivation	6	-3.18 (-9.13 to 2.77)	0.228	58.9	0.104
Restriction	12	-0.73 (-2.67 to 1.22)	0.428	11.5	0.186
Early restriction	6	-1.21 (-3.71 to 1.29)	0.268	< 0.001	0.752
Late restriction	6	-1.13 (-6.07 to 3.81)	0.583	61.6	0.035
Lower-body					
Deprivation	21	-3.25 (-5.09 to -1.41)	0.002	54.7	< 0.001
Restriction	25	-4.50 (-10.2 to 1.17)	0.114	72.8	< 0.001
Early restriction	20	-1.36 (-3.81 to 1.09)	0.259	6.97	0.892
Late restriction	5	-8.26 (-20.4 to 3.90)	0.132	81.7	< 0.001

Deprivation: participants did not sleep for an extended period of time (i.e., whole night); restriction: total sleep time ≤ 6 h in any 24 h period—this category is a combination of early restriction, late restriction, fragmented sleep and sleep restriction protocols not specified; early restriction: participants delayed sleep (i.e., went to sleep at a later time); late restriction; participants awakened earlier than normal

CI confidence interval

were only two outcome measures available for early restriction. Endurance performance tended to be affected (Table 3) by sleep loss, irrespective of the time of day exercise tasks were performed (AM or PM).

No significant relationships between time awake prior to completing the exercise task and the $\%_\Delta$ in endurance performance were identified in meta-regression analyses with any of the sleep-loss protocols (Table 4).

3.8 Strength-Endurance

Five studies ($n = 62$; 100% male), providing nine outcome measures, were included in this analysis. The overall weighted mean effect estimate (Table 2) indicated a negative influence of sleep loss on strength-endurance (mean $\%_\Delta = -9.85\%$, 95% CI -19.6 to -0.13, $p = 0.048$, $I^2 = 85.4\%$) [ESM Fig. S7]. However, the magnitude and statistical significance of the effect was unstable during one-out analyses (mean $\%_\Delta$ range $= -11.2$ to -8.71% and 95% CIs did not include zero except when outcome measures from six trials were sequentially removed [60, 75, 84, 86]). Findings were comparable with alternative correlation coefficients (ESM Table S14).

Subgroup analyses showed that strength-endurance was negatively affected by sleep restriction, but not sleep deprivation (Table 2). Note, however, that the three outcome measures analysed for sleep restriction were derived from one study [84]. There were no outcome measures to conduct analysis for either early- or late-restriction sleep protocols.

There were insufficient outcome measures to conduct meta-regression analyses on this exercise category.

3.9 Skill

Nine studies ($n = 146$; 80% male), providing 13 outcome measures, were included in this analysis. The overall weighted mean effect estimate (Table 2) indicated a negative influence of sleep loss on skill (mean $\%_\Delta = -20.9\%$, 95% CI -27.0 to -14.9, $p < 0.001$, $I^2 = 94.1\%$) [ESM Fig. S8]. The magnitude and statistical significance of the effect were stable during one-out (mean $\%_\Delta$ range $= -22.6$ to -19.2% and 95% CIs did not include zero) and sensitivity analyses (ESM Table S15).

Subgroup analyses showed that skill performance was negatively affected irrespective of the sleep-loss protocol (Table 2) or whether tasks were performed in the AM or PM. Note, there were insufficient outcome measures to conduct meta-analysis for late restriction.

No significant relationships between time awake prior to completing the task and $\%_\Delta$ in skill performance were identified in meta-regression analyses for any of the sleep-loss protocols (Table 4).

4 Discussion

The present systematic review and meta-analysis aimed to characterise the effects of acute sleep loss on exercise performance. We explored the influence of various contextual

factors, including the type of exercise task(s) performed, pattern of sleep loss incurred before exercise, time of day (AM or PM) the exercise task was performed, and length of time awake prior to undertaking the exercise task. Overall, our results indicate that acute sleep loss negatively impacts next-day exercise performance; however, the magnitude of the impact depends on the type of exercise performed, as well as which sleep-loss pattern precedes exercise. Total sleep loss (deprivation) and late restriction (early awakening) appear to have a larger effect on exercise performance than early restriction (delayed sleep). Results also suggest that exercise performed in the PM is more likely to be affected by sleep loss than exercise performed in the AM, and that the length of time awake prior to exercise is an influential factor.

4.1 Influence of Acute Sleep Loss on Exercise Performance

When all sleep-loss protocols (i.e., deprivation, restriction, early restriction, late restriction) were consolidated, our meta-analyses showed that acute sleep loss has a negative impact on all exercise categories (Table 2).

Tasks requiring a skill component appear to be particularly sensitive to the effects of sleep loss (mean $\%_\Delta = -20.9$, 95% CI -27.0 to -14.9) (Table 2). This may be attributed to the higher cognitive demand required to undertake skill performance tasks [133]. Sleep loss has been shown to alter discrete cognitive functions, including reaction time [99, 134], alertness [58], attention [134], memory [135], decision making [136, 137] and learning [138]. Thus, physical tasks that are also cognitively demanding are likely to be most affected by acute sleep loss.

A number of investigations have attempted to identify mechanisms explaining the relationship between sleep loss and impaired exercise performance. Studies have explored changes to cardiorespiratory variables (e.g., $\dot{V}O_{2peak}$ [49, 50, 120, 126, 132], ventilation [41, 49, 93, 110, 120, 126, 132], heart rate [41, 49, 50, 52, 91, 110, 120, 124, 126, 128, 132, 139], blood pressure [50]); perceived effort (measured via rating of perceived exertion) [41, 43, 44, 51, 52, 56, 57, 75, 86, 89–92, 95, 100, 110, 124, 132, 139]; muscle glycogen [91]; lactate [49, 67, 77, 91, 93, 95, 98, 124, 128, 139]; catecholamines [67, 121, 126]; hormones (cortisol [43, 55, 63, 67, 75, 84, 127], testosterone [63, 75, 84, 127], growth hormone [67], prolactin [67], melatonin [55], hepcidin [54], insulin [61]); body temperature (oral temperature [43, 45, 78, 79, 81, 90, 94, 95, 116] and core temperature [53, 80, 91, 110]); immune function [44, 50, 54, 62, 127]; and neural drive [60, 76, 86, 92]. However, it was not the intention of the present study to explore these mechanisms; rather our aim was to quantify the magnitude of effects that acute sleep loss has on exercise performance. As such, the reader is referred to the comprehensive review by Fullagar et al.

[36] on sleep and athletic performance for further details on the physiological responses associated with sleep loss.

4.2 Pattern of Sleep Loss

Another important finding in our study was the difference in the magnitude of change in performance when different types of sleep loss were analysed (i.e., deprivation, restriction, early and late restriction). We observed no change in exercise performance when early restriction sleep-loss protocols were isolated, except for skill and endurance tasks. For these two categories, the timing of the task should be considered (the influence of time of day is discussed in more detail in Sect. 4.3). For skill tasks, seven of eight outcome measures were performed in the PM. There were also only two outcome measures for endurance tasks and both were performed in the PM. Thus, individuals performing all other tasks (anaerobic power, speed/power endurance, HIIE, strength, and strength-endurance) appear able to maintain their performance under conditions of early sleep restriction.

In contrast to results identified with early-restriction protocols, the detrimental effects observed with sleep deprivation and late-restriction protocols appear to be more consistent and similar in magnitude. This may be a result of greater changes to one or more of the aforementioned mechanisms (highlighted in Sect. 4.1) underpinning exercise performance. Indeed, it may provide more opportunity to accrue particular aspects (e.g., fatigue [140]) when participants are kept awake or awoken early from sleep (i.e., in late-restriction protocols) until when the performance task is completed [36]. Given these results, when sleep loss is unavoidable and individuals have some level of control over timing, early restriction would appear preferable to late restriction. From a practical perspective, should an athlete need to travel, it would be reasonable for a health professional to recommend that it is better to do so the night before and sleep locally (even if that results in delayed sleep onset), rather than wake early for travel.

Our meta-regression analyses identified a significant negative relationship between the time awake prior to completing the exercise task and the $\%_\Delta$ EP for both sleep deprivation and late-restriction protocols (note, our interpretation of results for sleep deprivation is based on the removal of the influential outlier [85]). Specifically, we found that on average, exercise performance declined by ~0.4% per hour following sleep loss (note, this result is not inflated by the skill category because 8/13 of these tasks were performed following an early-restriction protocol). For example, if an individual rises early (e.g., ~0300 h) and performs a task 12 h later (~1500 h), then a ~5% decrease in performance may be anticipated. Overall, these results suggest that if exercise is to be performed after a period of sleep loss, it should be done as soon as practically possible.

4.3 Influence of Time of Day Exercise is Performed

Results of the current study suggest that exercise performed in the PM is likely to be more adversely affected by sleep loss than exercise performed in the AM (Table 3). The influence time of day has on exercise performance (without sleep loss) is well documented [70]. Evidence suggests that exercise performance may improve throughout the day for a number of tasks (skill [141–143], strength [144, 145], anaerobic power [81, 146–148], swimming [149, 150], and endurance tasks [151–153]), and this may be a consequence of physiological changes that occur with shifts in the circadian cycle (e.g., core temperature) [70, 154]. On this basis, one might anticipate that the negative impact of sleep loss may be offset when tasks are performed in the afternoon or evening. However, our results suggest that performing exercise in the PM (hence inducing a greater period between the start of sleep loss and the commencement of the task) appears to be a more significant moderator of exercise performance than changes associated with normal circadian rhythms. Therefore, in the setting of acute sleep loss, exercise should be scheduled to be performed soon after waking, before performance is potentially compromised by training in the PM.

4.4 Limitations and Future Direction

At present, we are unable to explore the relationship between sleep quality and next-day exercise performance. The majority (~98%) of included outcomes were obtained from studies that only assessed sleep 'quantity' (i.e., time spent asleep—more often reflected by 'time in bed'). Polysomnography (PSG) is considered the 'gold standard' sleep assessment technique, and can provide important information on sleep architecture (e.g., time spent in non-rapid eye movement and rapid eye movement sleep stages [155]). As such, future studies should employ PSG for monitoring sleep, which will permit further exploration of the relationship between sleep quality and next-day exercise performance.

In the present review, we were unable to determine the influence of fragmented sleep (i.e., one or more nocturnal awakenings [48]) on next-day performance. To our knowledge only one investigation has been conducted on fragmented sleep [49], despite reports suggesting this is something athletes often experience [20, 24]; thus, further research targeting this specific sleep pattern is warranted. We also dichotomised time of day for task completion as AM or PM, which prevented exploration of effects at more specific times (e.g., early- vs. mid-morning and afternoon vs. evening). Furthermore, only 8/227 outcomes were measured later than 1800 h [45, 50, 86, 97, 121, 128, 132]. Given that many sporting events are carried out during the evening, future research should investigate the influence of sleep loss on tasks performed after 1800 h.

The influence of sleep loss on performance in the present study was based on discrete task categories. However, in reality, many sports require using concurrent physical/cognitive attributes (e.g., soccer, football), where certain skill activities (e.g., shot at goal/target) are frequently performed following short maximal sprint efforts or brief spurts of maximal effort interspersed with short recovery periods (e.g., HIIE). As such, future studies should explore the influence of sleep loss on performance tasks that involve a combination of physical/cognitive attributes to enhance translation and ecological validity with respect to team sports.

Finally, we were unable to explore the influence of certain factors in our analyses, often because insufficient data were available. For example, only a small number of female participants were included in studies (~11%), precluding exploration of sex as a variable. Furthermore, we could not investigate the impact of consecutive days/nights of sleep loss on exercise performance, nor explore the influence of participant training status. These present as opportunities for future research to further our understanding of potential factors that may influence the effects of sleep loss on exercise performance.

5 Conclusion

Acute sleep loss appears to have a negative impact on next-day exercise performance. The magnitude of the effect may be greater when individuals experience either sleep deprivation or late restriction, and when performance tasks are conducted in the PM. Individuals can anticipate a ~0.4% decline in performance for every hour spent awake following acute sleep loss. Thus, incorporating lifestyle behaviours/strategies that limit the likelihood of experiencing sleep loss must be emphasised. However, if acute sleep loss is anticipated and unavoidable, individuals should, where possible, endeavour to mimic early-restriction sleep patterns rather than deprivation or late restriction, and prioritise exercise to the morning in an effort to maintain performance.

Declarations

References

1. Leong RLF, Cheng GH, Chee MWL, Lo JC. The effects of sleep on prospective memory: a systematic review and meta-analysis. Sleep Med Rev. 2019;47:18–27.
2. Baglioni C, Spiegelhalder K, Lombardo C, Riemann D. Sleep and emotions: a focus on insomnia. Sleep Med Rev. 2010;14(4):227–38.
3. Morselli LL, Guyon A, Spiegel K. Sleep and metabolic function. Pflugers Arch. 2012;463(1):139–60.
4. Besedovsky L, Lange T, Born J. Sleep and immune function. Pflugers Arch. 2012;463(1):121–37.
5. van Dalfsen JH, Markus CR. The influence of sleep on human hypothalamic-pituitary-adrenal (HPA) axis reactivity: a systematic review. Sleep Med Rev. 2018;39:187–94.
6. Adams RJ, Appleton SL, Taylor AW, Gill TK, Lang C, McEvoy RD, et al. Sleep health of Australian adults in 2016: results of the 2016 Sleep Health Foundation national survey. Sleep Health. 2017;3(1):35–42.
7. Walsh NP, Halson SL, Sargent C, Roach GD, Nedelec M, Gupta L, et al. Sleep and the athlete: narrative review and 2021 expert consensus recommendations. Br J Sports Med. 2020;55:356–68.
8. Cho Y, Ryu SH, Lee BR, Kim KH, Lee E, Choi J. Effects of artificial light at night on human health: a literature review of observational and experimental studies applied to exposure assessment. Chronobiol Int. 2015;32(9):1294–310.
9. Lohsoonthorn V, Khidir H, Casillas G, Lertmaharit S, Tadesse MG, Pensuksan WC, et al. Sleep quality and sleep patterns in relation to consumption of energy drinks, caffeinated beverages, and other stimulants among Thai college students. Sleep Breath. 2013;17(3):1017–28.
10. Wetter DW, Young TB. The relation between cigarette smoking and sleep disturbance. Prev Med. 1994;23:328–34.
11. Fuller KH, Waters WF, Binks PG, Anderson T. Generalized anxiety and sleep architecture—a polysomnographic investigation. Sleep. 1997;20(5):370–6.
12. Prather AA, Carroll JE. Associations between sleep duration, shift work, and infectious illness in the United States: Data from the National Health Interview Survey. Sleep Health. 2021;7(5):638–43.
13. Sehgal A, Mignot E. Genetics of sleep and sleep disorders. Cell. 2011;146(2):194–207.
14. De Gennaro L, Marzano C, Fratello F, Moroni F, Pellicciari MC, Ferlazzo F, et al. The electroencephalographic fingerprint of sleep is genetically determined: a twin study. Ann Neurol. 2008;64(4):455–60.
15. Sargent C, Lastella M, Halson SL, Roach GD. How much sleep does an elite athlete need? Int J Sports Physiol Perform. 2021;16(12):1746–57.
16. Hoshikawa M, Uchida S, Hirano Y. A subjective assessment of the prevalence and factors associated with poor sleep quality amongst elite Japanese athletes. Sports Med Open. 2018;4(1):10.
17. Andrade A, Bevilacqua GG, Casagrande PO, Brandt R, Coimbra D. Prevalence of poor sleep quality in athletes before competition. Physician Sportsmed. 2021;49(2):137–42.
18. Drew M, Vlahovich N, Hughes D, Appaneal R, Burke LM, Lundy B, et al. Prevalence of illness, poor mental health and sleep quality and low energy availability prior to the 2016 Summer Olympic Games. Br J Sports Med. 2018;52(1):47–53.
19. Swinbourne R, Gill N, Vaile J, Smart D. Prevalence of poor sleep quality, sleepiness and obstructive sleep apnoea risk factors in athletes. Eur J Sport Sci. 2016;16(7):850–8.
20. Leeder J, Glaister M, Pizzoferro K, Dawson J, Pedlar C. Sleep duration and quality in elite athletes measured using wristwatch actigraphy. J Sports Sci. 2012;30(6):541–5.
21. de Souza Bleyer FT, Barbosa DG, Andrade RD, Teixeira CS, Felden EPG. Sleep and musculoskeletal complaints among elite athletes of Santa Catarina. Rev Dor. 2015;16(2):102–8.
22. George CFP, Kab V, Kab P, Villa JJ, Levy AM. Sleep and breathing in professional football players. Sleep Med. 2003;4(4):317–25.
23. Gupta L, Morgan K, Gilchrist S. Does elite sport degrade sleep quality? A systematic review. Sports Med. 2017;47(7):1317–33.
24. Juliff LE, Halson SL, Peiffer JJ. Understanding sleep disturbance in athletes prior to important competitions. J Sci Med Sport. 2015;18(1):13–8.
25. Kecklund G, Axelsson J. Health consequences of shift work and insufficient sleep. BMJ. 2016;355: i5210.
26. Grandou C, Wallace L, Fullagar HHK, Duffield R, Burley S. The effects of sleep loss on military physical performance. Sports Med. 2019;49(8):1159–72.
27. Sargent C, Lastella M, Halson SL, Roach GD. The impact of training schedules on the sleep and fatigue of elite athletes. Chronobiol Int. 2014;31(10):1160–8.
28. Sargent C, Halson S, Roach GD. Sleep or swim? Early-morning training severely restricts the amount of sleep obtained by elite swimmers. Eur J Sport Sci. 2014;14:S310–5.
29. Buguet A. Sleep under extreme environments: effects of heat and cold exposure, altitude, hyperbaric pressure and microgravity in space. J Neurol Sci. 2007;262(1–2):145–52.
30. Fowler P, Duffield R, Howle K, Waterson A, Vaile J. Effects of northbound long-haul international air travel on sleep quantity and subjective jet lag and wellness in professional Australian soccer players. Int J Sports Physiol Perform. 2015;10(5):648–54.
31. Fullagar HHK, Duffield R, Skorski S, White D, Bloomfield J, Kolling S, et al. Sleep, travel, and recovery responses of national footballers during and after long-haul international air travel. Int J Sports Physiol Perform. 2016;11(1):86–95.

32. Pickering C, Kiely J. What should we do about habitual caffeine use in athletes? Sports Med. 2019;49(6):833–42.

33. Haack M, Mullington JM. Sustained sleep restriction reduces emotional and physical well-being. Pain. 2005;119(1–3):56–64.

34. Gingerich SB, Seaverson ELD, Anderson DR. Association between sleep and productivity loss among 598 676 employees from multiple industries. Am J Health Promot. 2018;32(4):1091–4.

35. Engle-Friedman M. The effects of sleep loss on capacity and effort. Sleep Sci. 2014;7(4):213–24.

36. Fullagar HHK, Skorski S, Duffield R, Hammes D, Coutts AJ, Meyer T. Sleep and athletic performance: The effects of sleep loss on exercise performance, and physiological and cognitive responses to exercise. Sports Med. 2015;45(2):161–86.

37. Jones JJ, Kirschen GW, Kancharla S, Hale L. Association between late-night tweeting and next-day game performance among professional basketball players. Sleep Health. 2019;5(1):68–71.

38. Dinges DF. An overview of sleepiness and accidents. J Sleep Res. 1995;4(2):4–14.

39. Mullins HM, Cortina JM, Drake CL, Dalal RS. Sleepiness at work: a review and framework of how the physiology of sleepiness impacts the workplace. J Appl Psychol. 2014;99(6):1096–112.

40. Reilly T, Piercy M. The effect of partial sleep deprivation on weight-lifting performance. Ergonomics. 1994;37(1):107–15.

41. Chase JD, Roberson PA, Saunders MJ, Hargens TA, Womack CJ, Luden ND. One night of sleep restriction following heavy exercise impairs 3-km cycling time-trial performance in the morning. Appl Physiol Nutr Metab. 2017;42(9):909–15.

42. Axelsson J, Ingre M, Kecklund G, Lekander M, Wright KP, Sundelin T. Sleepiness as motivation: a potential mechanism for how sleep deprivation affects behavior. Sleep. 2020;43(6):1–6.

43. Khemila S, Abedelmalek S, Romdhani M, Souissi A, Chtourou H, Souissi N. Listening to motivational music during warming-up attenuates the negative effects of partial sleep deprivation on cognitive and short-term maximal performance: effect of time of day. Chronobiol Int. 2021;38(7):1052–63.

44. Romdhani M, Hammouda O, Chaabouni Y, Mahdouani K, Driss T, Chamari K, et al. Sleep deprivation affects post-lunch dip performances, biomarkers of muscle damage and antioxidant status. Biol Sport. 2019;36(1):55–65.

45. Edwards BJ, Waterhouse J. Effects of one night of partial sleep deprivation upon diurnal rhythms of accuracy and consistency in throwing darts. Chronobiol. 2009;26(4):756–68.

46. Kosmadopoulos A, Sargent C, Darwent D, Zhou X, Roach GD. Alternatives to polysomnography (PSG): a validation of wrist actigraphy and a partial-PSG system. Behav Res Methods. 2014;46(4):1032–41.

47. Reynolds AC, Banks S. Total sleep deprivation, chronic sleep restriction and sleep disruption. Prog Brain Res. 2010;185:91–103.

48. Luboshitzky R, Zabari Z, Shen-Orr Z, Herer P, Lavie P. Disruption of the nocturnal testosterone rhythm by sleep fragmentation in normal men. J Clin Endocrinol Metab. 2001;86(3):1134–9.

49. Mougin F. Effects of sleep disturbances on subsequent physical performance. Eur J Appl Physiol. 1991;63:77–82.

50. Rae DE, Chin T, Dikgomo K, Hill L, McKune AJ, Kohn TA, et al. One night of partial sleep deprivation impairs recovery from a single exercise training session. Eur J Appl Physiol. 2017;117(4):699–712.

51. Roberts SSH, Teo WP, Aisbett B, Warmington SA. Extended sleep maintains endurance performance better than normal or restricted sleep. Med Sci Sports Exerc. 2019;51(12):2516–23.

52. Roberts SSH, Teo WP, Aisbett B, Warmington SA. Effects of total sleep deprivation on endurance cycling performance and heart rate indices used for monitoring athlete readiness. J Sports Sci. 2019;37(23):2691–701.

53. Bambaeichi E, Reilly T, Cable NT, Giacomoni M. The influence of time of day and partial sleep loss on muscle strength in eumenorrheic females. Ergonomics. 2005;48(11–14):1499–511.

54. Goto K, Mamiya A, Ito H, Maruyama T, Hayashi N, Badenhorst CE. Partial sleep deprivation after an acute exercise session does not augment hepcidin levels the following day. Physiol Rep. 2020;8(10).

55. Goh VHH, Tong TYY, Lim CL, Low ECT, Lee LKH. Effects of one night of sleep deprivation on hormone profiles and performance efficiency. Mil Med. 2001;166(5):427–31.

56. Ajjimaporn A, Ramyarangsi P, Siripornpanich V. Effects of a 20-min nap after sleep deprivation on brain activity and soccer performance. Int J Sports Med. 2020;41(14):1009–16.

57. Cullen T, Thomas G, Wadley AJ, Myers T. The effects of a single night of complete and partial sleep deprivation on physical and cognitive performance: a Bayesian analysis. J Sports Sci. 2019;37(23):2726–34.

58. Daaloul H, Souissi N, Davenne D. Effects of napping on alertness, cognitive, and physical outcomes of karate athletes. Med Sci Sports Exerc. 2019;51(2):338–45.

59. Moore J, McDonald C, McIntyre A, Carmody K, Donne B. Effects of acute sleep deprivation and caffeine supplementation on anaerobic performance. Sleep Sci. 2018;11(1):2–7.

60. Skurvydas A, Zlibinaite L, Solianik R, Brazaitis M, Valanciene D, Baranauskiene N, et al. One night of sleep deprivation impairs executive function but does not affect psychomotor or motor performance. Biol Sport. 2020;37(1):7–14.

61. Sweeney EL, Peart DJ, Kyza I, Harkes T, Ellis JG, Walshe IH. Impaired insulin profiles following a single night of sleep restriction: the impact of acute sprint interval exercise. Int J Sport Nutr Exerc Metab. 2020;30(2):139–44.

62. Abedelmalek S, Chtourou H, Aloui A, Aouichaoui C, Souissi N, Tabka Z. Effect of time of day and partial sleep deprivation on plasma concentrations of IL-6 during a short-term maximal performance. Eur J Appl Physiol. 2013;113(1):241–8.

63. Cook CJ, Crewther BT, Kilduff LP, Drawer S, Gaviglio CM. Skill execution and sleep deprivation: effects of acute caffeine or creatine supplementation—a randomized placebo-controlled trial. J Int Soc Sports Nutr. 2011;8(2).

64. Souissi N, Chtourou H, Aloui A, Hammouda O, Dogui M, Chaouachi A, et al. Effects of time-of-day and partial sleep deprivation on short-term maximal performances of judo competitors. J Strength Cond Res. 2013;27(9):2473–80.

65. Vardar SA, Öztürk L, Kurt C, Bulut E, Sut N, Vardar E. Sleep deprivation induced anxiety and anaerobic performance. J Sports Sci Med. 2007;6:532–7.

66. Mejri MA, Hammouda O, Zouaoui K, Chaouachi A, Chamari K, Rayana MCB, et al. Effect of two types of partial sleep deprivation on Taekwondo players' performance during intermittent exercise. Biol Rhythm Res. 2013;45(1):17–26.

67. Mougin F, Bourdin H, Simon-Rigaud ML, Nguyen NU, Kantelip JP, Davenne D. Hormonal responses to exercise after partial sleep deprivation and after a hypnotic drug-induced sleep. J Sports Sci. 2001;19(2):89–97.

68. Kredlow MA, Capozzoli MC, Hearon BA, Calkins AW, Otto MW. The effects of physical activity on sleep: a meta-analytic review. J Behav Med. 2015;38(3):427–49.

69. Thomas C, Jones H, Whitworth-Turner C, Louis J. High-intensity exercise in the evening does not disrupt sleep in endurance runners. Eur J Appl Physiol. 2020;120(2):359–68.

70. Thun E, Bjorvatn B, Flo E, Harris A, Pallesen S. Sleep, circadian rhythms, and athletic performance. Sleep Med Rev. 2015;23:1–9.

71. Knowles OE, Drinkwater EJ, Urwin CS, Lamon S, Aisbett B. Inadequate sleep and muscle strength: Implications for resistance training. J Sci Med Sport. 2018;21(9):959–68.

72. Pilcher JJ, Huffcutt AI. Effects of sleep deprivation on performance: a meta-analysis. Sleep. 1996;4:318–26.

73. Moher D, Shamseer L, Clarke M, Ghersi D, Liberati A, Petticrew M, et al. Preferred reporting items for systematic review and meta-analysis protocols (PRISMA-P) 2015 statement. Syst Rev. 2015;4:1.

74. Assink M, Wibbelink CJM. Fitting three-level meta-analytic models in R—a step-by-step tutorial. Tutor Quant Methods Psychol. 2016;12(3):154–74.

75. Blumert PA, Crum AJ, Ernsting M, Volek JS, Hollander DB, Haff EE, et al. The acute effects of twenty-four hours of sleep loss on the performance of national-caliber male collegiate weightlifters. J Strength Cond Res. 2007;21(4):1146–54.

76. Gonçalves A, Teodosio C, Pezarat-Correia P, Vila-Chã C, Mendonca VG. Effects of acute sleep deprivation on H reflex and V wave. J Sleep Res. 2021;30(6):e13118.

77. Souissi M, Abedelmalek S, Dhiba DB, Nikolaidis PT, Ben Awicha H, Chtourou H, et al. Morning caffeine ingestion increases cognitive function and short-term maximal performance in footballer players after partial sleep deprivation. Biol Rhythm Res. 2015;46(5):617–29.

78. Souissi M, Chtourou H, Abedelmalek S, Ben Ghozlane I, Sahnoun Z. The effects of caffeine ingestion on the reaction time and short-term maximal performance after 36 h of sleep deprivation. Physiol Behav. 2014;131:1–6.

79. Souissi M, Souissi Y, Mseddi E, Sahnoun Z. The effects of caffeine on the diurnal variation of the reaction time and short-term maximal performance after one night of sleep deprivation. Biol Rhythm Res. 2019;52(10):1–16.

80. Souissi N, Sesboue B, Gauthier A, Larue J, Davenne D. Effects of one night's sleep deprivation on anaerobic performance the following day. Eur J Appl Physiol. 2003;89:359–66.

81. Souissi N, Souissi M, Souissi H, Chamari K, Tabka Z, Dogui M, et al. Effect of time of day and partial sleep deprivation on short-term. High-Power Output Chronobiol Int. 2008;25(6):1062–76.

82. Kujawa K, Olpinska-Lischka M, Maciaszek J. The influence of 24-hour sleep deprivation on the strength of lower limb muscles in young and physically fit women and men. Sustainability. 2020;12(7).

83. Bulbulian R, Heaney JH, Leake CN, Sucec AA, Sjoholm NT. The effect of sleep deprivation and exercise load on isokinetic leg strength and endurance. Eur J Appl Physiol Occup Physiol. 1996;73(3–4):273–7.

84. Cook C, Beaven CM, Kilduff LP, Drawer S. Acute caffeine ingestion's increase of voluntarily chosen resistance-training load after limited sleep. Int J Sport Nutr Exerc Metab. 2012;22(3):157–64.

85. Arazi H, Mehrabani J, Irandoost M, Khaleghimamaghani E. Effects of overnight sleep deprivation on appetite and physical performance in elite female soccer players. J Turk Sleep Med. 2019;6(3):93–7.

86. Arnal PJ, Lapole T, Erblang M, Guillard M, Bourrilhon C, Leger D, et al. Sleep extension before sleep loss: effects on performance and neuromuscular function. Med Sci Sports Exerc. 2016;48(8):1595–603.

87. Baati H, Chtourou H, Moalla W, Jarraya M, Nikolaidis PT, Rosemann T, et al. Effect of angle of view and partial sleep deprivation on distance perception. Front Psychol. 2020;11:201.

88. Baati H, Hmani MS, Jarraya M, Chtourou H, Masmoudi L, Trabelsi K, et al. Effect of total sleep deprivation on egocentric distance estimation following a fatiguing task. Biol Rhythm Res. 2015;46(2):265–74.

89. HajSalem M, Chtourou H, Aloui A, Hammouda O, Souissi N. Effects of partial sleep deprivation at the end of the night on anaerobic performances in judokas. Biol Rhythm Res. 2013;44(5):815–21.

90. Romdhani M, Hammouda O, Smari K, Chaabouni Y, Mahdouani K, Driss T, et al. Total sleep deprivation and recovery sleep affect the diurnal variation of agility performance- the gender differences. J Strength Cond Res. 2021;35(1):132–40.

91. Skein M, Duffield R, Edge J, Short MJ, Mundel T. Intermittent-sprint performance and muscle glycogen after 30 h of sleep deprivation. Med Sci Sports Exerc. 2011;43(7):1301–11.

92. Temesi J, Arnal PJ, Davranche K, Bonnefoy R, Levy P, Verges S, et al. Does central fatigue explain reduced cycling after complete sleep deprivation? Med Sci Sports Exerc. 2013;45(12):2243–53.

93. Mougin F, Bourdin H, Simonrigaud ML, Didier JM, Toubin G, Kantelip JP. Effects of a selective sleep deprivation on subsequent anaerobic performance. Int J Sports Med. 1996;17(2):115–9.

94. Ozturk L, Bulut E, Vardar SA, Uzun C. Effects of sleep deprivation on anaerobic exercise-induced changes in auditory brainstem evoked potentials. Clin Physiol Funct Imaging. 2007;27(5):263–7.

95. Romdhani M, Souissi N, Chaabouni Y, Mahdouani K, Driss T, Chamari K, et al. Improved physical performance and decreased muscular and oxidative damage with postlunch napping after partial sleep deprivation in athletes. Int J Sports Physiol Perform. 2020;15(6):874–83.

96. Skein M, Duffield R, Minett GM, Snape A, Murphy A. The effect of overnight sleep deprivation after competitive rugby league matches on postmatch physiological and perceptual recovery. Int J Sports Physiol Perform. 2013;8(5):556–64.

97. Souissi M, Chikh N, Affes H, Sahnoun Z. Caffeine reversal of sleep deprivation effects on alertness, mood and repeated sprint performances in physical education students. Biol Rhythm Res. 2018;49(5):746–60.

98. Souissi M, Souissi Y, Bayoudh A, Knechtle B, Nikolaidis PT, Chtourou H. Effects of a 30-min nap opportunity on cognitive and short-duration high-intensity performances and mood states after a partial sleep deprivation night. J Sports Sci. 2020;38(22):2553–61.

99. Taheri M, Arabameri E. The effect of sleep deprivation on choice reaction time and anaerobic power of college student athletes. Asian J Sports Med. 2012;3(1):15–20.

100. Daviaux Y, Mignardot JB, Cornu C, Deschamps T. Effects of total sleep deprivation on the perception of action capabilities. Exp Brain Res. 2014;232(7):2243–53.

101. Rodrigues R, de Azevedo FR, Teixeira B, Macedo R, Lopes A, Diefenthaeler F, et al. Combined and isolated effects of alcohol consumption and sleep deprivation on maximal strength, muscle endurance and aerobic exercise performance in healthy men: a cross-over randomized controlled trial. Sleep Biol Rhythms. 2021;19(4):433–41.

102. Romdhani M, Souissi N, Moussa-Chamari I, Chaabouni Y, Mahdouani K, Sahnoun Z, et al. Caffeine use or napping to enhance repeated sprint performance after partial sleep deprivation: why not both? Int J Sports Physiol Perform. 2021;16(5):711–8.

103. Chandler J, Cumpston M, Li T, Page MJ, Welch VA. Cochrane handbook for systematic reviews of interventions. Oxford: Wiley; 2019.

104. van Rosendal SP, Osborne MA, Fassett RG, Coombes JS. Guidelines for glycerol use in hyperhydration and rehydration associated with exercise. Sports Med. 2010;40(2):113–29.

105. Jadad AR, Moore A, Carroll D, Jenkinson C, Reynolds DJM, Gavaghan DJ, et al. Assessing the quality of reports of randomized clinical trials—is blinding necessary? Controll Clin Trials. 1996;17:1–12.

106. Maher CG, Moseley AM, Sherrington C, Elkins MR, Herbert RD. A description of the trials, reviews, and practice guidelines indexed in the PEDro database. Phys Ther. 2008;88(9):1068–77.

107. Verhagen AP, de Vet HC, de Bie RA, Kessels AG, Boers M, Bouter LM, et al. The Delphi list: a criteria list for quality assessment of randomized clinical trials for conducting systematic reviews developed by Delphi consensus. J Clin Epidemiol. 1998;51:1235–41.

108. Viechtbauer W. The metafor Package: A Meta-Analysis Package for R. 2021 [cited 24 Aug 2021]. https://www.metafor-project.org/doku.php

109. Filipas L, Ferioli D, Banfi G, La Torre A, Vitale JA. Single and combined effect of acute sleep restriction and mental fatigue on basketball free-throw performance. Int J Sports Physiol Perform. 2021;16(3):415–20.

110. Oliver SJ, Costa RJ, Laing SJ, Bilzon JL, Walsh NP. One night of sleep deprivation decreases treadmill endurance performance. Eur J Appl Physiol. 2009;107(2):155–61.

111. Holland GJ. Effects of limited sleep deprivation on performance of selected motor tasks. Res Q. 1968;39(2):285–94.

112. Higgins JPT, Green S. Cochrane handbook for systematic reviews of interventions; 2011.

113. Borenstein M, Hedges LV, Higgins JP, Rothstein HR. Introduction to meta-analysis. Oxford: Wiley; 2011.

114. Pickett GF, Morris AF. Effects of acute sleep and food deprivation on total body response time and cardiovascular performance. J Sports Med Phys Fitness. 1975;15(1):49–56.

115. Reilly T, Deykin T. Effects of partial sleep loss on subjective states, psychomotor and physical performance tests. J Hum Mov Stud. 1983;9(4):157–70.

116. Abedelmalek S, Boussetta N, Chtourou H, Souissi N, Tabka Z. Effect of partial sleep deprivation and racial variation on short-term maximal performance. Biol Rhythm Res. 2014;45(5):699–708.

117. Ricardo JSC, Cartner L, Oliver SJ, Laing SJ, Walters R, Bilzon JLJ, et al. No effect of a 30-h period of sleep deprivation on leukocyte trafficking, neutrophil degranulation and saliva IgA responses to exercise. Eur J Appl Physiol. 2009;105(3):499–504.

118. Roberson PA, Chase JD, Bigman MB, Saunders MJ, Luden ND, Womack CJ. Time of day, but not sleep restriction, affects markers of hemostasis following heavy exercise. Appl Physiol Nutr Metab. 2019;44(2):148–52.

119. Cullen T, Thomas G, Wadley AJ. Sleep deprivation: cytokine and neuroendocrine effects on perception of effort. Med Sci Sports Exerc. 2020;52(4):909–18.

120. Azboy O, Kaygisiz Z. Effects of sleep deprivation on cardiorespiratory functions of the runners and volleyball players during rest and exercise. Acta Physiol Hung. 2009;96(1):29–36.

121. Froberg JE, Karlsson C, Levi L, Lidberg L. Circadian rhythms of catecholamine excretion, shooting range performance and self-ratings of fatigue during sleep deprivation. Biol Psychol. 1975;2:175–88.

122. Hill DW, Borden DO, Darnaby KM, Hendricks DN. Aerobic and anaerobic contributions to exhaustive high-intensity exercise after sleep deprivation. J Sports Sci. 1994;12(5):455–61.

123. Reyner LA, Horne JA. Sleep restriction and serving accuracy in performance tennis players, and effects of caffeine. Physiol Behav. 2013;120:93–6.

124. Mejri MA, Yousfi N, Mhenni T, Tayech A, Hammouda O, Driss T, et al. Does one night of partial sleep deprivation affect the evening performance during intermittent exercise in Taekwondo players? J Exerc Rehabil. 2016;12(1):47–53.

125. Paryab N, Taheri M, H'Mida C, Irandoust K, Mirmoezzi M, Trabelsi K, et al. Melatonin supplementation improves psychomotor and physical performance in collegiate student-athletes following a sleep deprivation night. Chronobiol Int. 2021;38(5):753–61.

126. Chen H. Effects of 30-h sleep loss on cardiorespiratory functions at rest and in exercise. Med Sci Sports Exerc. 1991;23(2):193–8.

127. Dáttilo M, Antunes HKM, Galbes NMN, Mônico-Neto M, De Sá SH, Dos Santos Quaresma MVL, et al. Effects of sleep deprivation on acute skeletal muscle recovery after exercise. Med Sci Sports Exerc. 2020;52(2):507–14.

128. Omiya K, Akashi YJ, Yoneyama K, Osada N, Tanabe K, Miyake F. Heart-rate response to sympathetic nervous stimulation, exercise, and magnesium concentration in various sleep conditions. Int J Sport Nutr Exerc Metab. 2009;19:127–35.

129. Racinais S, Hue O, Blonc S, Le Gallais D. Effect of sleep deprivation on shuttle run score in middle-aged amateur athletes. Influence of initial score. J Sports Med Phys Fitness. 2004;44(3):246–8.

130. Brodan V, Kuhn E. Physical performance in man during sleep deprivation. J Sports Med Phys Fitness. 1967;7(1):28–30.

131. Khcharem A, Souissi M, Atheymen R, Ben Mahmoud L, Sahnoun Z. Effects of caffeine ingestion on 8-km run performance and cognitive function after 26 hours of sleep deprivation. Biol Rhythm Res. 2022;53(6).

132. Martin BJ. Effect of sleep-deprivation on tolerance of prolonged exercise. Eur J Appl Physiol Occup Physiol. 1981;47(4):345–54.

133. Dumer JS, Dinges DF. Neurocognitive consequences of sleep deprivation. Semin Neurol. 2005;25(1):117–29.

134. Jarraya M, Jarraya S, Chtourou H, Souissi N, Chamari K. The effect of partial sleep deprivation on the reaction time and the attentional capacities of the handball goalkeeper. Biol Rhythm Res. 2013;44(3):503–10.

135. Smith ME, McEvoy LK, Gevins A. The impact of moderate sleep loss on neurophysiologic signals during working-memory task performance. Sleep. 2002;25(7):56–66.

136. Harrison Y, Horne JA. The impact of sleep deprivation on decision making: a review. J Exp Psychol Appl. 2000;6(3):236–49.

137. Harrison Y, Horne JA. One night of sleep loss impairs innovative thinking and flexible decision making. Organ Behav Hum Decis Process. 1999;78(2):128–45.

138. Walker MP. Cognitive consequences of sleep and sleep loss. Sleep Med. 2008;9(Suppl 1):S29–34.

139. Mejri MA, Hammouda O, Zouaoui K, Chaouachi A, Chamari K, Rayana MCB, et al. Effect of two types of partial sleep deprivation on Taekwondo players' performance during intermittent exercise. Biol Rhythm Res. 2014;45(1):17–26.

140. Edwards B, Waterhouse J, Reilly T. The effects of circadian rhythmicity and time-awake on a simple motor task. Chronobiol Int. 2007;24(6):1109–24.

141. Deschodt VJ, Arsac LM. Morning vs. evening maximal cycle power and technical swimming ability. J Strength Cond Res. 2004;18(1):149–54.

142. Reilly T, Atkinson G, Edwards B, Waterhouse J, Farrelly K, Fairhurst E. Diurnal variation in temperature, mental and physical performance, and tasks specifically related to football (soccer). Chronobiol Int. 2007;24(3):507–19.

143. Rahnama N, Sajjadi N, Bambaeichi E, Sadeghipour HR, Daneshjoo H, Nazary B. Diurnal variation on the performance of soccer-specific skills. World J Sport Sci. 2009;2(1):27–30.

144. Coldwells A, Atkinson G, Reilly T. Sources of variation in back and leg dynamometry. Ergonomics. 1994;37(1):79–86.

145. Squarcini CF, Pires ML, Lopes C, Benedito-Silva AA, Esteves AM, Cornelissen-Guillaume G, et al. Free-running circadian rhythms of muscle strength, reaction time, and body temperature in totally blind people. Eur J Appl Physiol. 2013;113(1):157–65.

146. Reilly T, Down A. Circadian variation in the standing broad jump. Percept Mot Skills. 1986;62:830.

147. Bernard T, Giacomoni M, Gavarry O, Seymat M, Falgairette G. Time-of-day effects in maximal anaerobic leg exercise. Eur J Appl Physiol. 1998;77:133–8.

148. Souissi N, Gauthier A, Sesboue B, Larue J, Davenne D. Circadian rhythms in two types of anaerobic cycle leg

exercise: force-velocity and 30-s wingate tests. Int J Sports Med. 2004;25:14–9.

149. Baxter C, Reilly T. Influence of time of day on all-out swimming. Br J Sports Med. 1983;17:122–7.

150. Kline CE, Durstine JL, Davis JM, Moore TA, Devlin TM, Zielinski MR, et al. Circadian variation in swim performance. J Appl Physiol. 2007;102(2):641–9.

151. Reilly T, Baxter C. Influence of time of day on reactions to cycling at a fixed high intensity. Br J Sports Med. 1983;17:128–30.

152. Hill DW. Effect of time of day on aerobic power in exhaustive high-intensity exercise. J Sports Med Phys Fitness. 1996;36(3):155–60.

153. Bessot N, Nicolas A, Moussay S, Gauthier A, Sesboue B, Davenne D. The effect of pedal rate and time of day on the time to exhaustion from high-intensity exercise. Chronobiol Int. 2006;23(5):1009–24.

154. Shibata S, Tahara Y. Circadian rhythm and exercise. J Sports Med Phys Fitness. 2014;3(1):65–72.

155. Landry GJ, Best JR, Liu-Ambrose T. Measuring sleep quality in older adults: a comparison using subjective and objective methods. Front Aging Neurosci. 2015;7:166.