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REVIEW

How much does sleep deprivation impair endurance performance? A systematic review and meta-analysis

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ABSTRACT

We conducted a systematic review and meta-analysis to investigate the effect of sleep deprivation on endurance performance, as well as possible effect-modifying factors. Searches were done in Pubmed, Web of Science, Embase, and Scopus on 12 July 2022. We additionally searched the bibliographic references and citations on Google Scholar of the papers whose full text was analyzed. Eligible studies were randomized and non-randomized controlled trials that compared sleep deprivation and habitual-sleep night effects on endurance performance in healthy humans. The studies' quality was examined by the Cochrane Collaboration's risk of bias tool. We calculated the pooled standardized mean differences (pooled SMD) and 95% confidence interval (95%CI) by a random-effects model. A mixed-effects model analyzed subgroups. Thirty-one studies were analyzed ($n = 478$), generating 38 effect sizes in full. The overall risk of bias was low in 8% of the studies, unclear in 74%, and high in 18%. Sleep deprivation in general had a moderate negative effect on endurance performance (polled SMD [95%CI] = −0.52 [−0.67; −0.38]). Training status, sleep deprivation magnitude, assessment time, exercise mode, and endpoint type did not influence the sleep deprivation effect, whereas longer exercises (>30 min) were more affected by sleep deprivation than shorter ones ($P = 0.035$). Therefore, the available evidence supports that sleep deprivation's deleterious effect on endurance performance is of moderate size and depends on exercise duration. This information can be useful to estimate the performance decrement of endurance exercise practitioners under sleep deprivation in training routines and competitions.

PROSPERO registration number CRD42021229717.

Highlights:

- Sleep deprivation causes a moderate deleterious effect on endurance performance.
- Sleep deprivation similarly impairs endurance performance in untrained, recreationally-trained, and trained people, but its effect on well-trained and professional endurance athletes is unknown.
- One or more nights of partial sleep deprivation or one night of total sleep deprivation similarly compromise endurance performance. Uncertainties about the effect of more than one night of total sleep deprivation warrant more studies.
- Sleep deprivation impairs walking, running, and cycling endurance performance regardless of the exercise endpoint being unknown (i.e. incremental or constant load tests) or known (i.e. time trial tests) and assessment time. However, sleep deprivation causes a more deleterious effect on endurance performance in exercises lasting more than 30 min.

KEYWORDS
Aerobic performance; sleep-wake cycle; psychophysiology; exercise tolerance; sleepiness

Introduction

Sleep is a homeostatically regulated behaviour that allows restoring the neural, metabolic, and immune-endocrine functions demanded during the wakefulness period (Fullagar et al., 2015; Roberts et al., 2019c). However, many real-life circumstances can reduce the amount of sleep, thereby causing acute or chronic sleep deprivation (Ferrara & De Gennaro, 2001; Roberts et al., 2019c). While sleep deprivation generically refers to any reduction in the amount of sleep, partial and total sleep deprivation specifically refers to a reduction in habitual sleep time and a sleep absence during a 24 h period, respectively (Ferrara & De Gennaro, 2001). Sleep deprivation, in turn, can generate critical physiological and psychobiological effects that could impair endurance performance, here defined as the capacity

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to sustain whole-body dynamic and continuous exercise lasting more than 75 s (Fullagar et al., 2015; Massar et al., 2019; Roberts et al., 2019a; Van Cutsem et al., 2017).

Studies about sleep deprivation's effect on endurance performance have shown conflicting results. Suggested factors include small sample size, participants' endurance training status, sleep loss magnitude, assessment time, and exercise testing characteristics (Azboy & Kaygisiz, 2009; Craven et al., 2022; Cullen et al., 2019; Fullagar et al., 2015; Roberts et al., 2019a). A recent systematic review and meta-analysis have shown that sleep loss magnitude and assessment time did not influence the sleep deprivation deleterious's effect on endurance performance (Craven et al., 2022). However, it did not include studies with chronic sleep loss and did not consider a possible moderating effect of participants' endurance training status and exercise testing characteristics. Thus, a new systematic review of the literature followed by a meta-analysis could be valuable for reassessing the effect size and expanding possible effect modifiers. Accordingly, our primary aim was to determine whether sleep deprivation (acute and chronic) affects healthy humans' endurance performance by conducting a systematic review and meta-analysis of randomized and non-randomized controlled studies. Our secondary aim was to investigate whether endurance training status, sleep loss magnitude, assessment time, and exercise testing characteristics concerning exercise mode, endpoint type, and exercise duration influence the effect of sleep deprivation on endurance performance.

Methods

The present systematic review and meta-analysis was designed according to the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (Page et al., 2021), and the study's protocol is registered at the PROSPERO (CRD42021229717).

Eligibility criteria

The studies' eligibility was defined according to PICOS criteria. We included randomized and non-randomized controlled studies, which were carried out in healthy men and women, employed total or partial sleep deprivation for one or more nights, and somehow assessed endurance performance. The sleep deprivation condition must have been compared to a control condition involving a night with habitual sleep time. Studies were excluded when sleep deprivation was performed simultaneously with physical exercise, cognitive tasks, caloric restriction, or ingestion of pharmacological agents or placebo substances only in one study arm. We retrieved studies that used exercise testing (i.e. incremental, constant-load, and time-trial) commonly employed in laboratory and field to assess endurance performance (Currell & Jeukendrup, 2008). Only studies published in peer-reviewed journals and written in English were included in our analyses. There was no limit to the studies' publication date.

Search strategy

The original studies were retrieved from the electronic databases Pubmed, Web of Science, Embase, and Scopus on 12 July 2022. We combined the following terms in the searches (Supplementary Table 1): human, sleep deprivation, insufficient sleep, sleep fragmentation, fragmented sleep, sleep loss, restricted sleep, sleep restriction, sleep time, sleep duration, physical endurance, endurance performance, exercise tolerance, time to exhaustion, time to task failure, time-trial, aerobic exercise, endurance exercise, incremental exercise, progressive exercise, graded exercise, and exercise test.

Studies selection

Duplicate files retrieved from electronic databases were removed before the studies' selection (Mendeley version 1.19.4, Elsevier, Nederland). Thereafter, the studies were screened by titles and abstracts. If it was impossible to decide the studies' eligibility only by screening the title and abstract, the decision was made based on the full-text analysis. During this statge, we also conducted a backward and a forward search in the full-texts bibliographic references and studies that cited the full-texts on Google Scholar, respectively. Two researchers independently performed the studies' selection (T.R.L. and H.M.P.). Disagreements were resolved by consensus with a third researcher (B.M.S.).

Data extraction

One researcher (T.R.L.) extracted data in an Excel spreadsheet (Microsoft, USA). The spreadsheet was customized according to the data extraction model provided by the Cochrane group. A second researcher checked the extracted data (H.M.P.). Disagreements were resolved by consensus with a third researcher (B.M.S.).

Subjects' descriptions, sample size, sex, and maximal oxygen uptake ($\dot{V}O_2max$) were taken as descriptive data. We rated subjects' endurance training status based on the average $\dot{V}O_2max$ or subjects' descriptions, according to the criteria proposed by De Pauw et al. (2013). In one study (Cincin et al., 2015), the average

$\dot{V}O_2max$ was estimated based on the average of metabolic equivalents (MET) obtained via the Bruce protocol in the control condition. Sleep deprivation type (i.e. partial or total) and amount of nights in sleep deprivation were recorded for sleep deprivation characterization. In the studies with partial sleep deprivation, we also extracted the duration and moment (i.e. beginning, middle, or end) that sleep was interrupted. Exercise mode (i.e. running, walking, or cycling), protocol type (i.e. incremental, constant, or time-trial), and exercise duration were extracted for exercise testing characterization. When a warm-up phase preceded exercise testing without rest intervals between them, we considered the warm-up phase duration to determine the exercise duration. Moreover, we extracted the time of day the studies assessed the endurance performance (i.e. a.m. or p.m.).

Studies with more than one sleep deprivation condition, or that assessed the performance in more than one exercise test within their experimental design, had each sleep deprivation or exercise assessment condition treated separately (Chen, 1991; Cullen et al., 2019; Mougin et al., 2001; Omiya et al., 2009; Roberts et al., 2019b). One study evaluated different samples within their experimental design; therefore, we treated each sample as a different study (Azboy & Kaygisiz, 2009). These studies have been listed as "1", "2", or "3" regarding each condition.

Mean and standard deviation of the main outcome (i.e. endurance performance) were extracted from the intervention (i.e. sleep deprivation) and control (i.e. full-sleep night) conditions. Data reported as standard error were converted to standard deviation by multiplying the standard error by the square root of the sample size. In two studies, mean and standard deviation were calculated (Excel, Microsoft, USA) based on individual data presented in the full text (Holland, 1968; Martin, 1981). In one study (Bond et al., 1986), endurance performance data were extracted from the graph in triplicate using an online tool (Web Plot Digitizer, Version 4.1, USA). The average of three extractions was retained for analysis. One study did not report the peak workload achieved on an incremental exercise test but reported the $\dot{V}O_2max$ (Plyley et al., 1987). Given that peak power output and $\dot{V}O_2max$ are strongly associated in this type of exercise protocol (Porszasz et al., 2003), we used the $\dot{V}O_2max$ as the endurance performance parameter. Endurance performance data were insufficient in two studies (Racinais et al., 2004; Rodrigues et al., 2021), but the first authors provided additional data by e-mail. The first and last authors of one study were contacted by e-mail and ResearchGate to provide the standard deviation data of endurance performance in both experimental conditions, but we got no response (Souissi et al., 2020b). Then, we calculated the standard deviation by the t-value reported in the study. It was impossible to obtain the exercise duration in two papers (Holland, 1968; Plyley et al., 1987) and the time of day that endurance performance was assessed in three papers (Holland, 1968; Tanabe et al., 1998; Tanabe et al., 1999).

Risk of bias

Cochrane Collaboration's tool for assessing the risk of bias in randomized trials was used to assess eligible studies' risk of bias (Higgins et al., 2011). To generate a risk of bias score, we assigned 10, 5, and 0 points for low, unclear, and high risk of bias ratings, respectively. Two researchers independently performed the risk of bias assessment (T.R.L. and H.M.P.). Disagreements were resolved by consensus with a third researcher (B.M.S.).

Statistical analysis

Standardized mean differences (SMD) as Hedges' g and 95% confidence interval (95%CI) were calculated for endurance performance contrasting sleep deprivation and control conditions in each study. In the studies that used distance or work-based time-trial tests, the test outcome was inverted between experimental conditions (Chase et al., 2017; Khcharem et al., 2022a; Roberts et al., 2019a, 2019b), so that worse performance was always represented as negative values. Given that included studies had low sample sizes, methodological differences, and dependence between effect sizes (Harrer et al., 2021), we ran a meta-analysis using a random-effects model and a three-level model to calculate the overall effect (i.e. pooled SMD and 95% CI). The likelihood ratio test compared the meta-analytical models. The following classification was used to interpret the pooled SMD: 0.20, small; 0.50, moderate; and 0.80, large (Cohen, 1988). Between-studies heterogeneity was assessed by Cochran's Q and I^2 statistics. The following values were used to interpret I^2: lower than 50%, low heterogeneity; between 51% and 75%, moderate heterogeneity; and higher than 75%, high heterogeneity (Higgins et al., 2003). Publication bias was assessed by visual inspection of the Funnel plot asymmetry, Egger's intercept test, and trim-and-fill method. A meta-regression was calculated between the risk of bias score and the SMD of each study. A mixed-effects model analyzed the subgroups. The analyses were performed in R with the packages dmetar, metafor, and meta (Harrer et al., 2021). Statistical significance was set as $P < 0.05$.

Results

Studies selection

The search in the electronic databases returned 736 studies (Figure 1). After excluding 291 duplicate files, the 445 remaining studies were examined by title and abstract. Of these, 392 studies were excluded because they clearly did not meet the eligibility criteria. The full texts of the 53 remaining studies were examined. During the full-texts analysis, 15 studies were identified as potentiality eligible by bibliographic references (backward search) and Google Scholar (forward search). Thirty-seven studies were excluded from the full-texts analysis (Supplementary Table 3). Therefore, 31 studies were included in the systematic review and meta-analysis. The agreement among the researchers responsible for the studies' selection was 96%.

Studies characteristics

The characteristics of the studies included in the systematic review and meta-analysis are shown in Supplementary Table 2. Most studies were randomized controlled trials (19 studies). In total, 478 people participated in the studies (24 women and 454 men). Most studies were carried out with 10 or fewer subjects (mode: 10 subjects). We did not find studies conducted with well-trained and professional endurance athletes. The studies conducted with untrained, recreationally trained, and trained participants were 32%, 32%, and 36%, respectively.

In the 11 partial sleep deprivation studies, the amount of sleep lost was approximately two, three, four, five, or six hours. The sleep loss occurred at the beginning, end, or both sleep moments (i.e. beginning and end). In two studies, the moment of sleep loss occurred according to

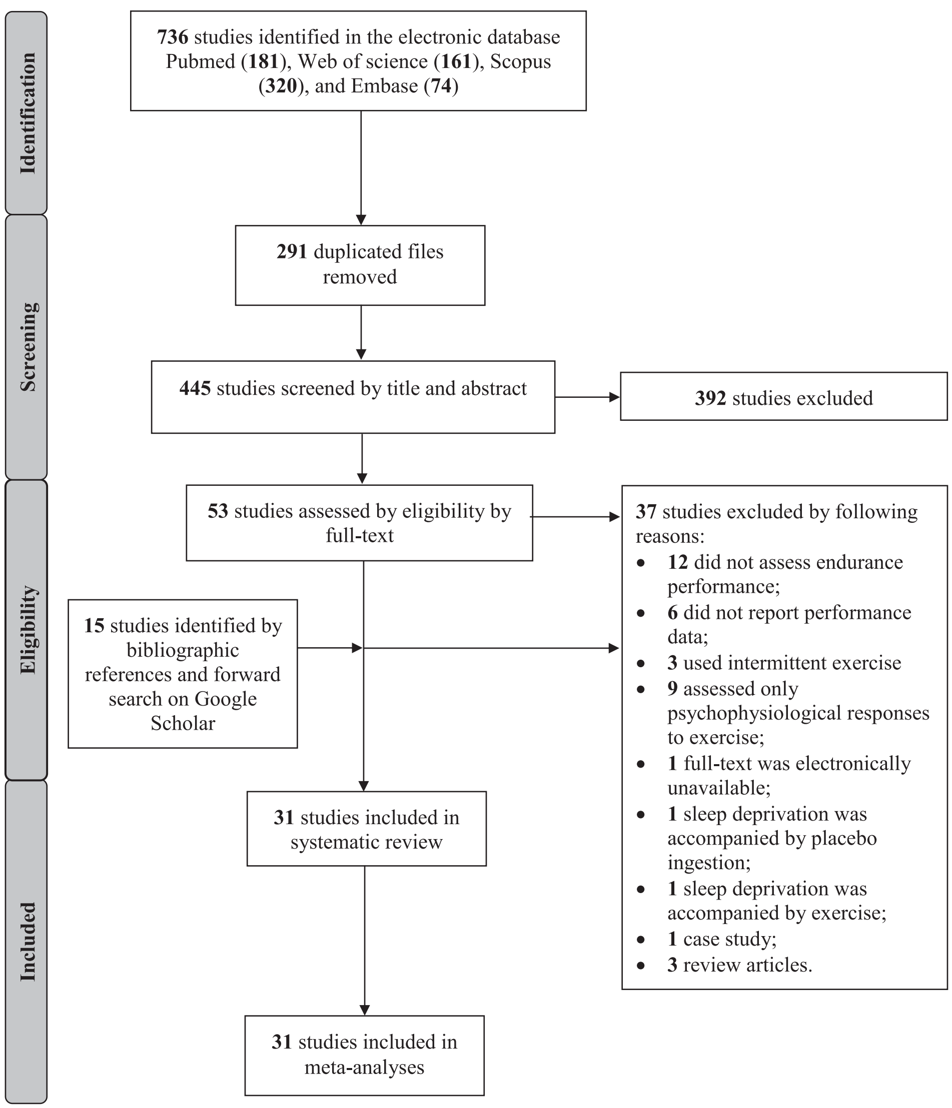

Figure 1. Fluxogram of studies selection.

participants' chronotype or after the onset of the rapid eye movement sleep phase (middle of sleep). In seven studies, partial sleep deprivation happened for one night, and in two studies for 30 nights. Two studies did one and more than one night of partial sleep deprivation. One of these studies deprived sleep by one and 35 nights and another by one, two, and three nights. Of 19 studies with total sleep deprivation, 15 deprived sleep for one night and four deprived sleep for two nights. One study had partial and total sleep deprivation, each for one night.

Fifteen studies assessed endurance performance before midday (a.m.) and 13 after midday (p.m.). The exercise mode used was cycling in 17 studies, running in 12, and walking in two. In 22 studies, the exercise endpoint was unknown; five used constant-load tests, and 17 used incremental exercise tests. One study used both incremental and constant-load exercise tests. Eight studies used time-trial tests (i.e. known endpoint); two were distance-based protocols, four were time-based, and two were work-based. The performance parameters were time (21 studies), distance (three studies), power output (five studies), number of shuttles (one study), and $\dot{V}O2max$ (one study). Exercise testing lasted more than 30 min in nine studies and less than 30 min in 20.

Risk of bias

Each study's risk of bias is shown in Figure 2. The agreement among the researchers responsible for the risk of bias analysis was 81%. The overall risk of bias was low, unclear, and high in 8%, 74%, and 18% of the studies, respectively (Supplementary Figure 1).

Meta-analysis

Sleep deprivation had a moderate negative effect on endurance performance based on random-effects model (Figure 3) and the three-level model (polled SMD [95% CI] = −0.53 [−0.68; −0.37]; t = −6.95; $P <$ 0.001; $\tau^2_{\text{Level 3}} = 0.033$). We found that the three-level model did not provide a significantly better fit than the random-effects model ($\chi^2_1 = 0.28$; $P = 0.599$). Between-studies heterogeneity was low in the random-effects model ($I^2 = 11.2\%$) and three-level model ($I^2_{\text{Level 3}} = 16.1\%$). The funnel plot's visual inspection (Supplementary Figure 2), Egger's intercept test (intercept = −1.10 [−2.62; −0.42]; t = −1.42; $P = 0.165$), and the trim-and-fill method did not indicate the presence of publication bias. Meta-regression did not find an association between the risk of bias score and SMD of each study ($\beta = -0.001$; $P = 0.874$; Supplementary Figure 3). Subgroup analyses showed that subjects' training status, sleep deprivation magnitude, assessment time, exercise mode, and exercise endpoint did not influence sleep deprivation's negative effect on endurance performance (Table 1). However, sleep deprivation had a greater negative effect on endurance performance in exercises lasting more than 30 min than in exercises lasting less than 30 min.

Discussion

The present systematic review and meta-analysis showed that sleep deprivation provoked a moderate impairment of endurance performance. This effect size seems to be accurate because 1) the effects' magnitude was moderate and the between-studies heterogeneity was low, independently of the meta-analytical model used to analyze the data, 2) there was no publication bias, and 3) bias scores were not associated with studies' effects in meta-regression analysis. Additionally, the present systematic review and meta-analysis found that endurance training status, sleep loss magnitude, assessment time, and exercise testing characteristics concerning exercise mode (i.e. walking, running, and cycling) and endpoint type (i.e. unknown and known) did not influence the sleep deprivation effect on endurance performance. However, exercises lasting more than 30 min were more negatively affected by sleep deprivation than shorter ones.

Sleep deprivation and endurance performance

Our data confirm the previous narrative reviews' conclusions and corroborate with the results of a recent systematic review and meta-analysis that sleep deprivation negatively affects endurance performance (Craven et al., 2022; Fullagar et al., 2015; Martin, 1986; Van Helder & Radomski, 1989). Furthermore, we add a reassessed and accurate estimate of the size of such a deleterious effect to the literature. Most of the analyzed studies had a relatively small sample size ($n \leq 10$), which can increase the chance of type II error (i.e. false negative) (Altman & Bland, 1995). Thus, we suggest that insufficient sample size was one of the main reasons for the lack of sleep deprivation effect on endurance performance in the analyzed studies, as was previously proposed by other authors (Cullen et al., 2019; Fullagar et al., 2015; Oliver et al., 2009; Souissi et al., 2020b). Of note, only two studies reported a sample size calculation (Rae et al., 2017; Vaara et al., 2018), and only one adequately justified the expected effect size (Rae et al., 2017). Failure to properly report the sample size calculation is common in exercise science (Bonafiglia et al., 2022). In this context, the current review provides valuable

Study	D1	D2	D3	D4	D5	D6	D7	Overral
Azboy & Kaygisiz (2009)1	-	-	x	-	+	-	-	-
Azboy & Kaygisiz (2009)2	-	-	x	-	+	-	-	-
Bond et al. (1986)	-	-	x	-	+	-	-	-
Chase et al. (2017)	-	-	x	-	+	-	+	-
Chen (1991)1	+	+	x	+	+	-	-	+
Chen (1991)2	+	+	x	+	+	-	-	+
Cincin et al. (2014)	-	-	x	+	+	-	+	-
Cullen et al. (2019)1	-	-	x	-	+	-	+	-
Cullen et al. (2019)2	-	-	x	-	+	-	+	-
Daanen et al. (2013)	+	-	x	-	+	-	-	-
Holland (1968)	x	x	x	-	+	-	-	x
Kazemizadeh & Behpour (2022)	+	-	x	-	+	-	-	-
Khcharem et al. (2022a)	-	-	x	+	+	-	-	-
Khcharem et al. (2022b)	-	-	x	+	+	-	-	-
Kolka et al. (1984)	-	-	x	-	+	-	-	-
Konishi et al. (2013)	-	-	x	-	+	-	+	-
Martin (1981)	-	-	x	x	+	-	-	-
Martin & Chen (1984)	-	-	x	-	+	-	-	-
Mougin et al. (1991)	-	-	x	-	+	-	+	-
Mougin et al. (2001)1	-	-	x	-	+	-	+	-
Mougin et al. (2001)2	-	-	x	-	+	-	+	-
Oliver et al. (2009)	-	-	x	-	+	-	+	-
Omiya et al. (2009)1	x	x	x	-	+	-	+	x
Omiya et al. (2009)2	x	x	x	-	+	-	+	x
Plyley et al. (1987)	x	x	x	-	+	-	-	x
Racinais et al. (2004)	x	x	x	-	+	-	-	x
Rae et al. (2017)	-	-	x	-	+	-	+	-
Roberts et al. (2019a)	-	-	x	-	+	-	+	-
Roberts et al. (2019b)1	-	-	x	-	+	-	+	-
Roberts et al. (2019b)2	-	-	x	-	+	-	+	-
Roberts et al. (2019b)3	-	-	x	-	+	-	+	-
Rodrigues et al. (2021)	+	-	x	+	+	-	+	+
Souissi et al. (2020)	-	-	x	-	+	-	+	-
Tanabe et al. (1998)	x	x	x	-	+	-	x	x
Tanabe et al. (1999)	x	x	x	-	+	-	x	x
Temesi et al. (2013)	-	-	+	+	+	-	+	-
Vaara et al. (2018)	x	x	x	-	-	-	-	-
Zhang et al. (2021)	-	-	x	-	-	-	+	-

Figure 2. Risk of bias classification according to Cochrane Collaboration's tool. D1, selection bias (random sequence generation); D2, selection bias (allocation concealment); D3, performance bias (blinding of participant and personnel); D4, detection bias (blinding of outcome assessment); D5, attrition bias (incomplete outcome data); D6, reporting bias (selective reporting); D7, other bias sources (sleep quantification). The bias of selection, detection, and other sources were key domains to assess the overall risk of bias. Symbols x, -, and + represent high, unclear, and low risk of bias, respectively. Numbers 1, 2, and 3 represent studies with more than one sleep deprivation condition, exercise type, or different samples within the experimental design (Supplementary Table 2).

information on the magnitude of effect size for sample size calculation in future studies on this topic. In addition, we recommend testing for sex differences in future studies. Biological differences between sexes might influence the magnitude of sleep 'deprivation's effect on endurance performance (Mong & Cusmano, 2016). Because few women participated in the retrieved studies, and these studies did not investigate between-sex differences, it was not feasible to address this question in the current systematic review and meta-analysis.

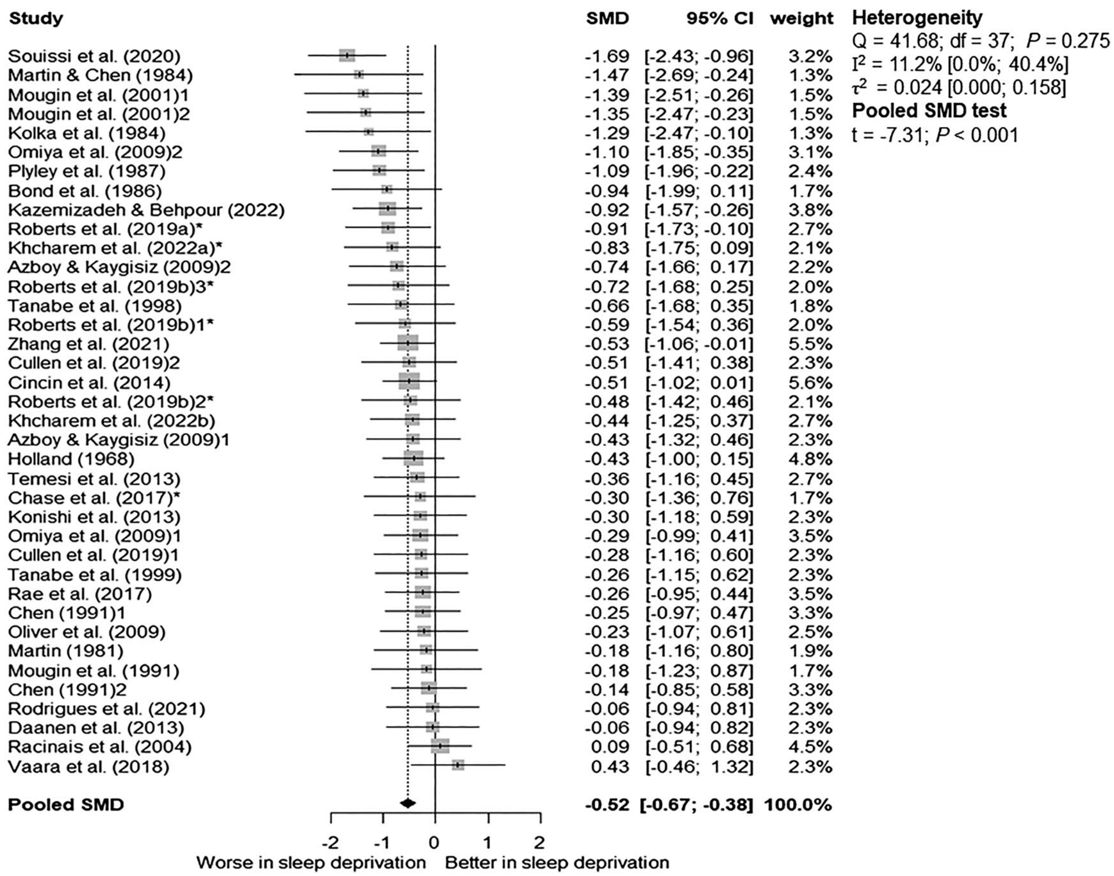

Figure 3. Forest plot showing the effect of sleep deprivation versus normal sleep on endurance performance. Numbers 1, 2, and 3 represent studies with more than one sleep deprivation condition, exercise type, or different samples within the experimental design (Supplementary Table 2). Asterisks represent studies where exercise performance was inverted between the experimental conditions because they used fixed distance- or work-based time-trial exercises; thus, a worse performance was always represented as a negative value. SMD, standardized mean difference calculated as Hedges' g. 95%CI, 95% confidence interval. A random-effects model was used to obtain the overall effect. Studies' weight was calculated by the inverse variance method.

The mechanisms that underlie the deleterious effect of sleep deprivation on endurance performance were not within the present study's aims. However, we noted that sleep deprivation caused either no change (Azboy & Kaygisiz, 2009; Konishi et al., 2013; Omiya et al., 2009; Rae et al., 2017; Vaara et al., 2018) or a decrease (Bond et al., 1986; Chen, 1991; Mougin et al., 1991; Omiya et al., 2009; Plyley et al., 1987; Tanabe et al., 1998; Tanabe et al., 1999) in aerobic parameters associated with endurance performance, such as the anaerobic threshold and $\dot{V}O_2$max. One possible explanation for such decrease might be the macro- and micro-endothelial dysfunction generated by sleep deprivation (Holmer et al., 2021), which could compromise the oxygen delivery to skeletal muscle and, consequently, the aerobic energy supply during exercise (Chen, 1991; Vaara et al., 2018). Moreover, we also noted that eight out of 10 studies that measured perceived effort reported a sleep deprivation-increasing effect (Bond et al., 1986; Martin, 1981; Oliver et al., 2009; Plyley et al., 1987; Roberts et al., 2019a, 2019b; Rodrigues et al., 2021; Souissi et al., 2020b; Temesi et al., 2013; Vaara et al., 2018). Such observation suggests that sleep deprivation might alter mechanisms specifically involved in the perceived effort formation. In this sense, the brain's adenosine pathway could play an important role (Martin et al., 2018). For example, adenosine antagonists can reduce perceived effort and improve endurance performance in sleep-deprived subjects (McLellan et al., 2004). Adenosine is a neuromodulatory molecule that inhibits the activity of neurons responsible for wakefulness; therefore, it is considered a sleep-inducing substance (Porkka-Heiskanen, 1999; Reichert et al., 2022). Over the day, adenosine accumulates in the brain and decreases during a subsequent sleep episode (Porkka-Heiskanen, 1999). Thus, sleep loss precludes the removal of accumulated adenosine in the brain, generating psychobiological effects like sleepiness, mood alteration, cognition impairment, and perceptual modification throughout the waking period

Table 1. Subgroups analysis.

Subgroup	K	pooled SMD [95%CI]	*P*	Q (p-value)	I^2 [95%CI]	*P′*
Training status						
Untrained	12	-0.37 [-0.59; -0.15]	<0.001	8.85 (0.64)	0% [0%; 58%]	0.071
Recreationally trained and trained	26	-0.62 [-0.81; -0.43]	<0.001	30.12 (0.22)	17% [0%; 49%]	
Untrained	12	-0.37 [-0.59; -0.15]	<0.001	8.85 (0.64)	0% [0%; 58%]	0.181
Recreationally trained	12	-0.60 [-0.82; -0.37]	<0.001	7.94 (0.72)	0% [0%; 58%]	
Trained	14	-0.64 [-0.96; -0.32]	<0.001	22.18 (0.05)	41% [0%; 69%]	
Sleep deprivation magnitude						
Partial one night	11	-0.63 [-0.97; -0.29]	<0.001	15.48 (0.12)	35% [0%; 68%]	0.231
Total one night	18	-0.40 [-0.56; -0.24]	<0.001	11.25 (0.84)	0% [0%; 50%]	
Partial more than one night	5	-0.68 [-1.10; -0.26]	<0.001	2.21 (0.70)	0% [0%; 79%]	
Total more than one night	4	-0.80 [-2.21; 0.61]	0.071	9.40 (0.02)	68% [7%; 89%]	
Performance assessment time						
Before midday	19	-0.52 [-0.69; -0.35]	<0.001	13.69 (0.75)	0% [0%; 49%]	0.804
After midday	16	-0.56 [-0.87; -0.25]	<0.001	27.42 (0.03)	45% [2%; 70%]	
Exercise mode						
Running and walking	14	-0.63 [-0.93; -0.32]	<0.001	22.94 (0.04)	43% [0%; 70%]	0.314
Cycling	24	-0.46 [-0.62; -0.30]	<0.001	17.77 (0.77)	0% [0%; 45%]	
Exercise endpoint						
Known endpoint	11	-0.64 [-0.96; -0.31]	<0.001	12.38 (0.26)	19% [0%; 59%]	0.346
Unknown endpoint	27	-0.48 [-0.64; -0.31]	<0.001	28.05 (0.36)	7% [0%; 40%]	
Exercise duration						
Lower than 30 min	24	-0.44 [-0.62; -0.25]	<0.001	28.19 (0.21)	18% [0%; 50%]	0.035
Higher than 30 min	12	-0.76 [-1.03; -0.48]	<0.001	8.00 (0.71)	0% [0%; 58%]	

K, number of studies; SMD [95%CI], standardized mean difference and 95% confidence interval obtained in the mixed-effects model; *P*, p-values of the overall effect test within subgroups; Q (p-value), Cochran's Q heterogeneity statistics with p-value; I^2 [95%CI], I^2 heterogeneity statistics and 95% confidence interval; *P′*, p-values obtained in the subgroups comparisons.

(Daanen et al., 2013; Edwards et al., 2007; Elmenhorst et al., 2017; Fullagar et al., 2015; Martin et al., 2018; Massar et al., 2019; Muginshtein-Simkovitch et al., 2015; Tokizawa et al., 2015).

Modifying factors

Endurance training status did not influence the sleep deprivation effect on endurance performance. This is an interesting finding since it has been hypothesized that endurance training status could mitigate the deleterious effect of sleep deprivation on endurance performance (Roberts et al., 2019a). It is important to note, however, that no evidence is available, according to the classification adopted in the present study, regarding well-trained and professional endurance athletes (De Pauw et al., 2013). Sleep deprivation appears to generate a mental fatigue state (Martin et al., 2018), but well-trained and professional endurance athletes seem to be more resistant to psychobiological alterations induced by mental fatigue (Lopes et al., 2020; Martin et al., 2016; Martin et al., 2018; Roberts et al., 2019a). Well-trained and professional endurance athletes could, therefore, be less affected by sleep deprivation. For instance, Roberts et al. (2019a) have shown a negative correlation (r = - 0.65) between the anaerobic threshold (aerobic fitness parameter) and the sleep deprivation-induced change in trained cyclists' and triathletes' cycling time-trial performance. Therefore, future studies involving well-trained and professional endurance athletes are warranted.

Similarly to Craven et al. (2022), we also found that partial and total sleep deprivation for one night generated similar detrimental effects on endurance performance. One could suppose that the severity of partial sleep deprivation in some studies or exercise testing protocol differences within each subgroup could justify our findings. However, we noticed that the sleep loss severity was well distributed among the partial sleep deprivation studies. Moreover, the low between-studies heterogeneity within subgroups suggests that exercise testing protocols or other circumstantial differences among the studies do not seem to have influenced the result. Our finding agrees with the only experimental study that compared the effect of partial and total sleep deprivation for one night on endurance performance (Cullen et al., 2019). The considerable overlap between the confidence intervals in this study suggests that both sleep loss patterns similarly impaired endurance performance. One possible explanation for our and Cullen et al.'s (2019) results might be a reduction in sleep quality when sleep duration is shorter (Cullen et al., 2019). A reduction in sleep duration may interfere with the proportion of time spent in each sleep phase

(Mougin et al., 1991; Mougin et al., 2001), thereby compromising sleep efficiency. Moreover, partial sleep deprivation could have a "floor" detrimental effect on endurance performance. Future studies could address such hypotheses.

Partial sleep deprivation during one or many nights might be closer to what happens in real-life circumstances in most non-athletes (Ferrara & De Gennaro, 2001) and athletes (Walsh et al., 2020). In this sense, our results revealed that one and more than one night of partial sleep deprivation similarly impaired endurance performance. The low between-studies heterogeneity within subgroups also discards the role of exercise testing protocols or other circumstantial differences among the studies in our result. The one-night subgroup had two studies that conducted a severe sleep deprivation protocol (> 5 h); however, their effects were not discrepant as compared to other studies included in analyses (Chase et al., 2017; Cincin et al., 2015). Experimentally, Roberts et al. (2019b) have shown a comparable impairment in cycling time-trial performance after one, two, and three nights of partial sleep deprivation. On the other hand, Omiya et al. (2009) have shown that the impairment in incremental cycling exercise performance was greater after 35 nights of partial sleep deprivation than after one night of partial sleep deprivation. Psychobiological alterations related to sleep deprivation (i.e. increased perceived effort and decreased motivation) could have favoured a more sedentary behaviour during the period between assessments in the study by Omiya et al. (2009), thereby causing the subject's detraining, which may have contributed to lower performance on the incremental cycling test at day 35 (Hagger et al., 2010; Massar et al., 2019; Oliver et al., 2009; Roberts et al., 2019a). Unlike studies investigating cognitive performance (Van Dongen et al., 2003), our finding, together with a previous study (Roberts et al., 2019b), suggest that there is not a cumulative effect of partial sleep deprivation on endurance performance. Nevertheless, researchers should conduct further studies to confirm such a hypothesis.

Many nights of total sleep deprivation are not typical in the general population (Ferrara & De Gennaro, 2001). This sleep loss pattern occurs on special occasions, for example, during sustained military operations (McLellan et al., 2016). Our results surprisingly indicated that more than one night of total sleep deprivation did not affect endurance performance. However, such a finding should be carefully interpreted because one study has found a positive non-significant effect of two nights of total sleep deprivation on endurance performance (Vaara et al., 2018). Together with the low amount of studies, such a result extended the overall effect size confidence interval of the more than one night of total sleep deprivation subgroup. Thus, this finding is very likely a false-negative result. In the same sense, the between-subgroup comparisons involving the subgroup with more than one night of total sleep deprivation should be interpreted cautiously.

Possibly because of the time awake, the psychobiological alterations (e.g. mood and cognition) are higher during the afternoon and evening than in the morning (Edwards et al., 2007; Elmenhorst et al., 2017). Consequently, sleep deprivation's deleterious effect should be more extensive in the studies that assessed endurance performance after midday. Indeed, sleep deprivation has been found to worsen afternoon, but not morning, anaerobic performance (Souissi et al., 2003; Souissi et al., 2008). However, in our study, the exercise testing time of day did not influence the sleep deprivation's deleterious effect on endurance performance. This result corroborates Craven et al.'s (2022) findings. One possible explanation for this paradoxical result might be a direct time of day effect on endurance performance. Previous studies have shown that endurance performance is better in the afternoon and evening (i.e. p.m.) as compared to morning (i.e. a.m.), possibly because of an improvement in aerobic metabolism (Fernandes et al., 2014; Souissi et al., 2020a). Thus, the positive influence of the afternoon and evening on endurance performance might compensate for the possible adverse effects of increased time awake. Future experimental studies should investigate this question since no study compared whether the time of day influences sleep deprivation's effect on endurance performance. Furthermore, people's chronotype influence on sleep deprivation's effect, as well as its interaction with the time of day, deserves investigation, as chronotype seems to modulate many sleep loss-related psychobiological alterations (Song et al., 2019). Evening-type individuals, for example, have been found to be more vulnerable to the impairment caused by total sleep deprivation on vigilance assessed during the morning (Song et al., 2019).

A recent narrative review suggested that differences between exercise testing protocols could explain divergent results in the literature about the effect of sleep deprivation on endurance performance (Fullagar et al., 2015). However, our subgroup analysis revealed sleep deprivation compromises endurance performance regardless of the mode and endpoint type of exercise. Complex motor tasks (e.g. running) and known endpoint exercises seem to require more from executive functions that are compromised by sleep deprivation, such as inhibitory control, sustained attention, and working memory (Brick et al., 2016; Lambourne & Tomporowski, 2010; Santos-Concejero et al., 2020). However, other factors that influence the regulation of endurance performance, regardless of the exercise testing protocol, are also affected by sleep deprivation (e.g. perception of effort, motivation, aerobic metabolism, and endothelial function) (Chen, 1991; Fullagar et al., 2015; Holmer et al., 2021; Lim & Dinges, 2010; Marcora & Staiano, 2010; Martin, 1981; Massar et al., 2019; Oliver et al., 2009). Thus, our results suggest that a complex interplay among several factors might mediate the deleterious effect of sleep deprivation on endurance performance, and differences in exercise protocols and their varying demands on executive functions might play a minor role.

Finally, our subgroup analysis showed that sleep deprivation caused a greater endurance performance impairment in exercises lasting longer than 30 min. During prolonged exercise, there is a progressive increase in thermal discomfort, possibly due to body temperature increase (Van Cutsem et al., 2019). Sleep deprivation compromises thermoregulation during prolonged exercise performed in a temperate environment, making heat loss difficult and accentuating body temperature increase (Sawka et al., 1984). Perhaps, for this reason, the perception of thermal discomfort is greater when exercise is performed under sleep deprivation (Muginshtein-Simkovitch et al., 2015; Tokizawa et al., 2015). Dealing with this increased thermal discomfort over time, in turn, could exacerbate the perception of effort (Van Cutsem et al., 2019), thereby further limiting endurance performance in exercise lasting longer than 30 min. Another possibility is the effect of sleep deprivation on motivational factors (Massar et al., 2019), which seem more relevant to limiting performance during prolonged endurance exercise (Iannetta et al., 2022).

Implications

Endurance exercise practitioners should avoid even minor sleep loss as much as possible. Improving sleep habits could be beneficial to achieving this goal (Walsh et al., 2020). Strategies to mitigate sleep deprivation's adverse effects on endurance performance are desirable, as sleep loss is sometimes unavoidable (Ferrara & De Gennaro, 2001; Roberts et al., 2019c). Examples are daytime napping and sleep extension on days preceding nights where sleep loss is expected (Keramidas et al., 2018; Roberts et al., 2019b). Caffeine has also been considered a strategy to mitigate sleep loss-induced reduction in exercise performance (McLellan et al., 2016). However, the effective dose seems to be substantially high (McLellan et al., 2016). Thus, endurance exercise practitioners should be careful when using caffeine to mitigate the adverse effects of sleep deprivation, as the high dosage required to establish positive effects could disrupt the subsequent night's sleep (Walsh et al., 2020).

Limitations

Only one study attempted to blind the subjects about the intervention, not telling the study's objectives (Temesi et al., 2013). We recognize this is a challenging task given the intervention's nature, but we cannot rule out that a negative expectation (i.e. nocebo effect) regarding the intervention could have enhanced the deleterious effect of sleep deprivation in the studies that did not control for the nocebo effect (Hurst et al., 2020). Most studies did not report whether the outcome assessor was blinded to the experimental conditions. Physical performance can be influenced by verbal incentives (Andreacci et al., 2002). Thus, the lack of assessor blinding is a potential bias, which could have been easily circumvented. The unclear risk of reporting bias in all studies, in part, can be explained by the fact that it is not common in the exercise science field to make a study registration (Bonafiglia et al., 2022). At last, some studies did not objectively assess sleep time, which should be taken into account by next studies via either polysomnography or actigraphy (Roberts et al., 2019c). Of note, meta-regression results guarantee the methodological limitations present in retrieved studies did not influence the overall sleep deprivation effect on endurance performance.

We included studies involving different sleep loss patterns and exercise testing characteristics. However, the low between-studies heterogeneity supports the methodological differences across the studies had little influence on results, thereby ensuring the validity of our (sub)analysis. Moreover, the number of effect sizes in some subgroup analyses is lower or close to the lower limit of the recommended (10) as a general rule of thumb (Harrer et al., 2021). Some results, therefore, should be interpreted with caution. Many included studies did not accurately report the amount of sleep loss. Therefore, we could not execute a meta-regression with the accumulated time of sleep debt. We did not include studies in which sleep deprivation simultaneously occurred with caloric restriction, physical tasks, and effortful cognitive activities. Our results, therefore, should not be extended for situations such as military sustained operations and ultra-endurance sports involving overnight physical activity and concurrent food intake or mentally demanding tasks. Finally, we attributed scores to test the influence of methodological limitations on the overall sleep deprivation effect. Other approaches have been proposed, such as subgroup analysis. However, an inadequate number of studies with a low risk of bias made this approach impossible.

Conclusion

The present systematic review and meta-analysis revealed that available evidence supports a moderate deleterious effect of sleep deprivation on endurance performance. The low between-studies heterogeneity, inexistent publication bias, and absence of association between studies' risk of bias and its effects ensure the robustness of the reported effect size. Moreover, sleep deprivation's deleterious effect on endurance performance occurred regardless of individuals' endurance training status, sleep loss magnitude, assessment time, and exercise testing characteristics concerning exercise mode (i.e. walking, running, and cycling), and endpoint type (i.e. unknown and known). However, exercises lasting more than 30 min are more negatively affected by sleep deprivation (moderate effect size) than exercises lasting less than 30 min (small effect size). Our results can help to estimate the performance decrement of endurance exercise practitioners under sleep deprivation in training routines and competitions. Future studies should involve well-trained and professional endurance athletes, simulate real-life sleep loss patterns, consider sex and people's chronotype influence, include adequate sample size, improve methodological rigour, and investigate underlining mechanisms.

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