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Review

Inadequate sleep and muscle strength: Implications for resistance training

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ABSTRACT

Objectives: Inadequate sleep (e.g., an insufficient duration of sleep per night) can reduce physical performance and has been linked to adverse metabolic health outcomes. Resistance exercise is an effective means to maintain and improve physical capacity and metabolic health, however, the outcomes for populations who may perform resistance exercise during periods of inadequate sleep are unknown. The primary aim of this systematic review was to evaluate the effect of sleep deprivation (i.e. no sleep) and sleep restriction (i.e. a reduced sleep duration) on resistance exercise performance. A secondary aim was to explore the effects on hormonal indicators or markers of muscle protein metabolism.

Methods: A systematic search of five electronic databases was conducted with terms related to three combined concepts: inadequate sleep; resistance exercise; performance and physiological outcomes. Study quality and biases were assessed using the Effective Public Health Practice Project quality assessment tool.

Results: Seventeen studies met the inclusion criteria and were rated as 'moderate' or 'weak' for global quality. Sleep deprivation had little effect on muscle strength during resistance exercise. In contrast, consecutive nights of sleep restriction could reduce the force output of multi-joint, but not single-joint movements. Results were conflicting regarding hormonal responses to resistance training.

Conclusion: Inadequate sleep impairs maximal muscle strength in compound movements when performed without specific interventions designed to increase motivation. Strategies to assist groups facing inadequate sleep to effectively perform resistance training may include supplementing their motivation by training in groups or ingesting caffeine; or training prior to prolonged periods of wakefulness.

1. Introduction

Sleep is essential for physiological and cognitive functioning.[1,2] Inadequate sleep, that is, when an insufficient duration or quality of sleep is obtained per night, is detrimental to health and work productivity.[2,3] As the world continues moving toward a 24-h society, more people are getting less sleep.[4] In recognition of this widespread issue, inadequate sleep has recently been declared as a 'public health problem' by the US Centres for Disease Control and Prevention.[1] It is estimated that inadequate sleep costs up to US$680 billion of economic output across the US, UK, Japan, Germany and Canada annually.[1] Lifestyle factors such as working prolonged or irregular hours, social commitments and family responsibilities can all contribute to inadequate sleep.[1]

Inadequate sleep may occur as a result of sleep deprivation, that is, a sustained state of wakefulness with no sleep, or sleep restriction, that is, a chronically reduced sleep duration.[5] Approximately 40% of adults experience inadequate sleep.[1,3] Athletes, new parents and older adults are particularly susceptible to sleep restriction or sleep deprivation. These groups experience disturbances to their sleep cycle (e.g. through training and competing at night, newborn feeding schedules or age-related sleep impairments) exposing them to frequent inadequate sleep. Shiftworkers, who work outside of a historically typical 7am to 6pm period[6] and experience different feeding patterns and light-exposure schedules compared to day-time workers, are also at risk of inadequate sleep.[2] Shiftworkers may sleep for a short duration or at a time that is mismatched with physiological functions exhibiting a circadian rhythm, a process known as circadian misalignment,[6] which can also result in

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inadequate sleep.[2] Inadequate sleep increases fatigue and reduces the physical capacity for daily tasks.[5] Sleeping less than 7 h per night is also associated with an increased risk of cardiovascular disease, type 2 diabetes and obesity by up to 48%.[2]

Physical capacity depends on several factors, including cardiovascular fitness and muscle strength. Muscle strength is critical for daily task capacity in new parents, older adults and shiftworkers, as well as for performance in athletes. Sustained resistance training increases muscle strength and physical capacity[7,8] and reduces risk factors for type 2 diabetes, obesity and cardiovascular disease,[9] which are over-represented in populations facing inadequate sleep. Bi-weekly resistance training is recommended for all adults, for short- and long-term health,[10] but these guidelines do not consider the potential impact of inadequate sleep or daily fluctuations in strength and training capacity,[11] nor how these factors interact with changes in motivation and the optimal times of day[12] or days on which to train.

Resistance exercise has a chronic positive effect on skeletal muscle mass,[13] which underpins muscle strength. Skeletal muscle fibres are made up of almost 90% of proteins.[14] Skeletal muscle mass is regulated by the fine balance between the rate of protein synthesis and the rate of protein degradation occurring in the muscle.[14] When this balance is maintained, muscle mass is preserved.[14] Resistance exercise is a potent way to increase skeletal muscle mass by triggering the molecular pathways that activate protein synthesis in the muscle.[13] Resistance exercise places mechanical load on the muscle, activating pathways that control muscle protein synthesis[13] in the cell. Resistance exercise also stimulates the release of hormones that directly promote protein synthesis (referred to as anabolic hormones), such as testosterone, growth hormone and insulin-like growth factor 1 (IGF-1).[15] At rest, these hormones fluctuate partially due to a circadian rhythm; the peak of their secretion often occurring at the onset of or during sleep.[12] Their secretion in response to resistance exercise positively influences muscle protein turnover,[15,16] allowing for increases in muscle mass and strength.

The prescription of resistance training may require particular care for groups who are likely to train in conditions of inadequate sleep or misalignment between their sleep time and endogenous circadian rhythm. Our group[17] recently hypothesised that an altered sleep–wake cycle may be detrimental to skeletal muscle health. Indeed, inadequate sleep increases the levels of hormones that directly promote protein degradation (referred to as catabolic hormones), such as cortisol, and decreases the levels of anabolic hormones in the blood.[17] By disturbing baseline muscle protein metabolism,[17] inadequate sleep may blunt skeletal muscle adaptations to resistance exercise. Previous reviews[18,19] have found extended sleep deprivation can reduce muscle strength in athletes, yet have focused on providing recommendations to optimise sleep. While improved sleep outcomes are critical for athletes, the training, work and lifestyle demands of these and other groups could make sleep restriction unavoidable in some circumstances. If resistance exercise is going to be a viable strategy to improve and maintain physical capacity and preserve metabolic health, prescription guidelines specific to groups facing inadequate sleep are imperative. Therefore, the primary aim of this review is to evaluate the literature investigating the impact of inadequate sleep on resistance exercise performance; a secondary aim is to explore the consequences for regulators of muscle protein metabolism.

2. Methodology

2.1. Search strategy

This review was conducted using the preferred reporting items for systematic reviews and meta-analyses (PRISMA) statement.[20] A systematic search of the electronic databases EBSCOHost (searching Academic Search Complete, Medline Complete, Global Health SPORTdiscus), Embase, Scopus, Web of Science and PubMed was used to identify peer-reviewed, English-language studies of relevance, since inception. The key words for the search were as follows: *sleep deprivation*; *sleep loss*; *sleep restriction*; *circadian*; *diurnal*; *time of day*; *shift work*; *night shift*; *insufficient sleep*; *inadequate sleep*; *sleep fragmentation*; *sleep interruptions*; *sleep restoration*; *sleep extension* and *nocturnal* searched together with *resistance training*; *resistance exercise*; *strength training*; *weight training*; *physical training*; *physical conditioning*; *weight lifting*; *calisthenics*; *concentric*; *eccentric*; *isotonic* and *isometric* searched together with *performance*; *physical performance*; *muscle*; *muscle strength*; *muscle mass*; *hormone*; *cortisol*; *testosterone*; *protein synthesis*; *recovery*; *growth*; *IGF-1*; *insulin* and *metabolism.* Search terms were phrased and truncated as appropriate.

2.2. Eligibility criteria

The eligibility criteria required studies to investigate the effect of inadequate sleep on resistance exercise (e.g. handgrip test) or training performance outcomes. Outcome measures of interest were muscle strength and physiological response mechanisms underlying changes in muscle strength or size e.g. hormonal indicators or markers of protein metabolism. Title/s and abstracts were screened for relevance to sleep and resistance exercise in adults and potentially relevant articles were accessed to assess the full text. Studies were excluded if no nocturnal sleep loss occurred or if the sleep deprivation or restriction period was not defined. Animal studies and conference abstracts were also excluded. Screening, data extraction and quality assessment were performed by two authors (OK, CU). Disagreement on any article or outcome was discussed between authors and resolved by additional authors (ED, SL, BA) where required.

2.3. Quality assessment

The Effective Public Health Practice Project (EPHPP) quality assessment tool for quantitative studies[21] was used to assess the methodological strength of each study. Standard scoring procedures were used to assign global scores based on the accumulation of strong, moderate or weak scores given across domains of selection bias, study design, confounders, blinding, data collection method, and withdrawals and dropout[21] (Table 2).

3. Results

3.1. Literature selection

The original search presented 1702 peer-reviewed, English-language articles, of which 997 were identified as duplicates (Fig. 1). Screening of titles/abstracts excluded 669 articles irrelevant to sleep loss and/or strength parameters. Twelve articles were retrieved from reference lists of relevant articles. Thirty-one articles were excluded where the outcome measures were deemed irrelevant, were conference abstracts or the full text could not be retrieved. Studies investigating jetlag and Ramadan have been previously reviewed[22,23] and were therefore excluded. The final number of studies included in this review was 17. The study characteristics and key findings are presented in Table 1. The quality assessment scores for each paper, based on the EPHPP tool, are shown in Table 2.

3.2. Sleep restriction

Seven studies investigated one night of sleep restriction[24–30] and one study examined repeated nights (three or more) of

Table 1
Characteristics and key findings of studies related to inadequate sleep and resistance exercise.

Authors	Sample size (*n*), PA status	Age (mean ± SD), sex	Amount of sleep (protocol[a])	Exercise protocol	Time of testing	Outcome measures	Key findings[b]
Arnal et al.[32]	12, physically active	32.3 ± 3.9, M	5 nights of EXT *or* HAB, followed by 1 night TSD	Strength test pre (D0) & post (D1) TSD	1700 h	Isometric knee extension (time to exhaustion), knee extension MVC	*TSD compared to control night* ↓ pre-exercise MVC (HAB, $d = -1.38$; EXT $d = -0.33$) ↓ time to exhaustion (HAB, $d = -1.31$; EXT $d = -0.52$) *EXT compared to HAB* ↔ pre-exercise MVC ↑ time to exhaustion ($d = 0.51$ at D0, $d = 0.74$ at D1)
Bambaeichi et al.[24]	8, sedentary	30.0 ± 6.0, F	2.5 h sleep for 1 night (delayed sleep onset)	Strength test	0600 h & 1800 h	MVC & isokinetic knee extension & flexion peak torque	*SR compared to control night* ↔ MVC or isokinetic peak to torque ↔ interaction between SR & time of day
Blumert et al.[36]	9, national level weight lifters	20.7 ± 1.2, M	1 night TSD	RT session: snatch, clean & jerk, front squat; 6–7 sets, 1–2reps; 70–100% 1-RM (additional submaximal sets for front squat after 1-RM set)	0900 h	1RM, volume load & training intensity. Blood samples (C, T)	*TSD compared to control night* ↔ 1RM, total volume load, total training intensity ↔ T, C, T/C ratio
Bougard et al.[28]	11, N/A	21.5 ± 1.5, N/A	5 *or* 6 h sleep for 1 night (early waking)	Strength tests	0600 h	MVC & isometric elbow flexion strength (mean torque)	*5-h SR compared to 6-h SR* ↔ MVC or isometric mean torque
Bulbulian et al.[39]	24, marine corps	TSD/EX group: 22.1 ± 2.9, M TSD group: 21.7 ± 2.2, M	1 night TSD (with or without EX)	Strength tests. 40 km march carrying 50% BW performed during TSD for TSD/EX group	1600 h	Isokinetic knee extension & flexion (peak torque & fatigue index)	*TSD compared to control night* ↓ knee extension peak torque ↔ fatigue index *TSD/EX compared to control night* ↓ knee extension & flexion peak torque ↔ fatigue index
Chase et al.[27]	7, recreational cyclists	24.0 ± 7.0, 6 M & 1 F	3 h sleep for 1 night, (early waking)	Strength tests 60 min cycle sprint interval session & leg press	0830 h	Isokinetic knee extension (peak torque)	*SR compared to control night* ↔ peak torque

Table 1 (*Continued*)

Authors	Sample size (n), PA status	Age (mean ± SD), sex	Amount of sleep (protocol[a])	Exercise protocol	Time of testing	Outcome measures	Key findings[b]
Cook et al.[30]	16, professional rugby players	20.9 ± 0.9, M	<6 h sleep (protocol not reported)	RT session: squat, bench press, bench row; 4 sets, repetitions to failure; 85% 1-RM	1100 h	Total workload (volume x intensity) & saliva samples (C, T)	*SR compared to control night* ↓ total workload ($d = 2.33$) ↑ baseline C ($d = 0.41\text{-}0.80$) ↔ post-RT C ↓ baseline ($d = 0.67\text{-}1.09$) and post-RT T *SR (with caffeine) compared to SR (placebo)* ↑ total workload ($d = 1.47$) ↑ post-RT T ↑ post-RT C
Daviaux et al.[33]	24, N/A	21.4 ± 5.3, 12 M & 12 F	1 night TSD	Strength tests	0800 h & 2000 h	Knee extension & MVC	*TSD compared to control group* ↔ MVC strength ↔ interaction between TSD & time of day
Goh et al.[34]	14, military service members	20–30, M	1 night TSD	Strength tests	0800, 1300 h & every 3 h from 1800–600 h	Handgrip strength & saliva samples (C)	*TSD compared to control group* ↔ handgrip strength ↑ C at 1330 h only
HajSalem et al.[26]	21, judo athletes	19.1 ± 1.2, M	4.5 h sleep for 1 night (early waking)	Strength tests pre- & post-judo match	N/A	Handgrip strength	*SR compared to control night* ↔ handgrip strength
Meney et al.[35]	11, N/A	20–28, M	1 night TSD (day 1), followed by 1 night normal sleep (day 2)	Strength tests	Day 1: every 4 h from 0600–0200 h. Day 2: every 4 h from 1000–2200 h	Handgrip, knee extension & back extension strength	*TSD compared to control night* ↔ day 1 handgrip & knee strength, ↓ back strength at 2am only ↓ day 2 back strength
Reilly & Piercy[31]	8, trained	18–24, M	3 h sleep each night, for 3 nights (delayed sleep onset)	Bicep curl, bench press, dead lift, leg press	1700 h	1-RM	*TSD compared to control night* ↓ 1RM deadlift, leg press, bench press ↔ 1RM bicep curl
Skien et al.[37]	11, amateur rugby league athletes	20.4 ± 2.5, M	1 night TSD	Strength tests Rugby match ~7 h after pre-match test and before TSD period	Pre-match (8000 h), Post-match, 2 h & 16 h post-match	MVC & voluntary activation of knee extensors.	*TSD compared to control night* ↔ MVC ($d = 0.13\text{-}0.33$) & voluntary activation ($d = 0.16\text{-}0.56$)

Souissi et al.[25]	12, judo athletes	18.6 ± 2.4, M	3 h sleep for 1 night (delayed sleep onset *or* early waking)	Strength tests pre- & post-judo match	0900 h & 1600 h	Handgrip strength & elbow flexor MVC	*Early waking SR compared to control night* ↓ Handgrip strength (3.1-8.4%) & MVC in the evening (15-24%) *Delayed onset SR compared to control night* ↔ Handgrip strength & MVC
Symons et al.[40]	11, N/A	22.0 ± 3.0, M	2 nights of TSD	Strength tests	1100 h: isokinetic tests	Bench press & leg extension strength (for 25 repetitions), elbow flexor & leg extensor MVC	*TSD compared to control night*
				6 h hike between night 1 & 2 of TSD	1400: MVC tests		↔ bench press & leg extension peak torque ↔ MVC
Takeuchi et al.[38]	12, strength trained	22.7 ± 2.2, M	2 nights of TSD	Strength tests	0000 h	Handgrip strength, isokinetic leg flexion & extension (peak torque)	*TSD & TSD/EX compared to control night*
				1 h of treadmill walking at 28% VO$_2$ max every 3 h for TSD/EX group			↓ knee extension torque at 60° s^{-1} *TSD compared to TSD/EX* ↔ handgrip strength, knee flexion or extension torque
Waterhouse et al.[29]	10, N/A	23.3 ± 3.4, M	4 h sleep for 1 night (early waking)	Strength test (with or without prior nap)	1400	Handgrip strength	*Nap compared to no-nap* ↔ handgrip strength

M, male; F, female; *n*, number; PA, physical activity; N/A, not available; SD, standard deviation; TSD, total sleep deprivation; SR, sleep restriction; EXT, extended sleep; HAB, habitual sleep; TSD/EX, total sleep deprivation & exercise; MVC, maximal voluntary contraction; RT, resistance training; RTD, rate of torque development; h, hour; ms, milliseconds; min, minutes; km, kilometre .T, testosterone; C, cortisol; BW, body weight; VO$_2$ max, maximal oxygen uptake; ↔, no effect ($p > 0.05$); ↓, significantly decreased ($p < 0.05$); ↑, significantly increased ($p < 0.05$); *d*, Cohen's *d* (representative of effect size, reported where available).

[a] Sleep restriction studies only.

[b] Key findings compared to a 'control night' indicate a within-groups study design whereas a 'control group' indicates a between-groups study design.

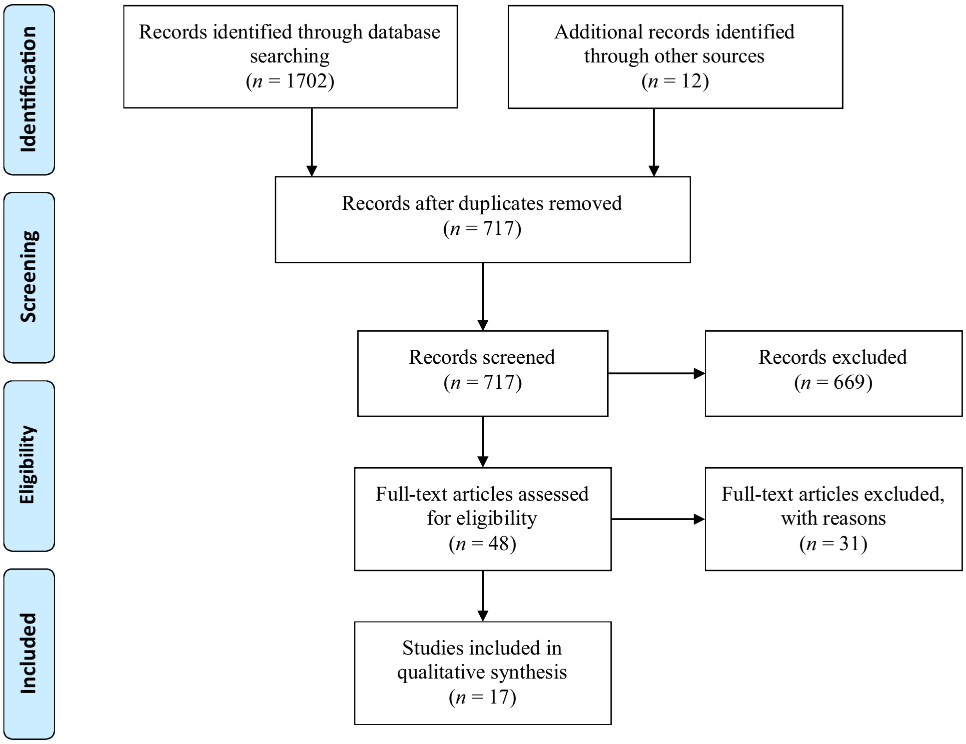

Fig. 1. Flow diagram summarising study selection process. n = number.

Table 2

Quality assessment of studies using the Effective Public Health Practice Project (EPHPP) quality assessment tool for quantitative studies.

Study	Selection bias	Study design	Confounders	Blinding	Data Collection Method	Withdrawals and dropout	Global score
Arnal et al.[32]	2	1	1	3	1	1	Moderate
Bambaeichi et al.[24]	1	2	1	3	1	1	Moderate
Blumert et al.[36]	2	1	1	3	1	1	Moderate
Bougard et al.[28]	1	1	1	3	1	3	Weak
Bulbulian et al.[39]	1	1	1	3	1	1	Moderate
Chase et al.[27]	2	1	1	3	1	1	Moderate
Cook et al.[30]	1	1	1	3	1	1	Moderate
Daviaux et al.[33]	1	1	2	3	1	1	Moderate
Goh et al.[34]	1	1	3	3	1	1	Weak
HajSalem et al.[26]	1	1	3	3	1	1	Weak
Meney et al.[35]	2	1	3	3	1	2	Weak
Reilly & Piercy[31]	2	1	1	3	2	1	Moderate
Skien et al.[37]	1	1	1	3	1	1	Moderate
Souissi et al.[25]	1	1	1	3	1	1	Moderate
Symons et al.[40]	2	1	1	3	1	1	Moderate
Takeuchi et al.[38]	1	1	1	3	1	1	Moderate
Waterhouse et al.[29]	2	1	2	3	1	1	Moderate

1 = strong; 2 = moderate; 3 = weak; Global scores were determined by the accumulation of domain scores for each paper. A ‘strong’ global score was given where studies had no ‘weak’ domain ratings, a moderate global score was given where studies had one ‘weak’ domain rating and a weak global score was given where studies had two or more ‘weak’ domain ratings.

sleep restriction.[31] Sleep opportunities varied from 2.5–6 h across studies, with two implementing delayed bedtime[24,31] and four implementing advanced waking protocols.[26–29] Souissi et al.[25] compared both advanced waking and delayed bedtime protocols. Time of testing varied from morning (0600 h) to late afternoon (1700 h). Most studies achieved ‘moderate’ EPHPP scores since sleep restriction studies cannot blind participants. Two studies achieved ‘weak’ global scores for not providing information regarding the control of confounders[26] and for a high participant non-completion rate[28] in addition to a lack of blinding.

Reilly and Piercy[31] exposed male participants to three nights of sleep restriction (sleep opportunity between 0300–0600 h). Sleep restriction significantly and linearly decreased one repetition maximum (RM) strength for leg press and deadlift (at 1700 h) after each successive night. Maximal bench press strength decreased after the third night only. Total workload performed during a resistance training session decreased with one night of sleep restriction (~6 h, time N/A).[30] The resistance training (at 1100 h) included four sets of repetitions to failure at 85% 1-RM for squat, bench press and bent row exercises. However, one night of sleep restriction (at ~0300–0600 h) demonstrated no effect on isometric and isokinetic knee extension and flexion strength in females (at 0600 and 1800 h)[24] or handgrip and elbow flexor strength in males (at 0900 and 1600 h).[25] Advanced waking protocols (at ~2300–0300) demonstrated no effect on maximal handgrip strength,[26] isokinetic leg extension torque[27] and isometric elbow flexor strength[28] when tested in the morning. A significant decrease by 3–8% in handgrip strength and 15–24% in elbow flexor MVC following advanced waking (at 2300–0200 h), was only found when strength tests were conducted in the afternoon.[25] Waterhouse et al.[29] used an advanced waking protocol (at ~2300–0300 h) in conjunction with or without a day time nap; napping had no effect on handgrip strength (at 1400 h). Elevated baseline cortisol and decreased baseline and post-exercise testosterone concentrations were attributed to sleep restriction in one study.[30] Collectively, these studies[25,30,31] indicate that multiple nights of sleep restriction or an extended wake time (e.g. more than twelve hours awake) following advanced waking impair muscle strength and disturb the hormonal response to resistance exercise.

3.3. *Sleep deprivation*

Six studies investigated the effect of one night of sleep deprivation on resistance exercise.[32–37] Four studies[32,33,36,37] were considered of 'moderate' quality and two studies[34,35] were unclear in their control of confounders and did not blind participants, resulting in 'weak' scores. Time of testing varied between studies, with tests conducted in the morning (~0800 h),[33] in the afternoon (~1700 h)[32] or at regular intervals (e.g. every 4 h) throughout the intervention.[34,35]

Blumert et al.[36] found that sleep deprivation (24 h) had no effect on 1-RM achieved or total workload during a resistance training session (at 0900 h). Similarly, sleep deprivation (24–40 h) had no effect on maximal voluntary contraction (MVC) tests of handgrip,[34] knee extension[33] and back extension strength,[35] tested periodically. In contrast, Arnal et al.[32] observed a significant performance decrease for knee extension MVC (at 1700 h) following sleep deprivation (34–37 h). One study[37] investigated the effect of sleep deprivation (24 h) following an afternoon rugby match with no effect on leg extensor MVC or voluntary activation. Sleep deprivation (24 h) demonstrated no effect on cortisol, testosterone or the cortisol–testosterone ratio following a resistance training session.[36] However, salivary cortisol levels in sleep-deprived military personnel increased only at 1330 h in comparison to control participants who slept overnight.[34] The findings demonstrate that maximal muscle strength and cortisol-testosterone profiles are typically maintained with a single night of sleep deprivation and resistance exercise.

Three studies[38–40] investigated the effect of sleep deprivation on muscle strength in conjunction with different exercise protocols and all received 'moderate' EPHPP quality ratings. Sleep deprivation (64 h) elicited a significant ≈19% decrease in knee extension torque (at 0000 h) with no mediating effect of intermittent treadmill walking.[38] Bulbulian et al.[39] found a significant decrease in peak knee extension torque (at 1600 h) amongst sleep-deprived (30 h) US Marine Corps personnel, and an additional decrease in knee flexion in those who also completed a 40-km march with external load. In contrast, Symons et al.[40] found a 6-h hike during 60 h of sleep deprivation had no effect on upper body or lower body isokinetic (at 1100 h) and MVC strength (at 1400 h), compared to a control group who slept at night. Overall, these results are not conclusive regarding the effect of sleep deprivation with extended exercise protocols on muscle strength.

4. Discussion

The following sections discuss the effect of sleep restriction and sleep deprivation on muscle strength and hormonal indicators of muscle protein metabolism, with the aim to provide context for specific populations facing inadequate sleep and implications for their training.

4.1. *Muscle strength in response to sleep restriction*

Three consecutive nights of sleep restriction impaired maximal force output where larger muscle groups were recruited.[31] Compound, multi-joint exercises that recruit large muscle groups are considered to be the most effective in increasing muscle strength.[41] The ability to adapt to resistance exercise rather than execute acute absolute strength is critical for preserving metabolic health; a reduced force output induced by sleep restriction could, over time, diminish the positive impact of resistance training on metabolic health. The findings are applicable to those facing frequent inadequate sleep, such as new parents or athletes in heavy training and competition. No shiftwork studies identified in the original search reported participants' sleep opportunities or quantity and were therefore excluded. The sleep–wake schedules and circadian rhythms of shiftworkers are likely to be different to other populations, therefore the applicability of day-oriented findings to shiftworkers, should be taken with caution. However, night-shiftworkers' rate of torque development during knee flexion has been demonstrated to decrease by 13.9%, when tested after a 36-h work period, compared to day-shiftworkers.[42] Therefore, consecutive night shifts may also reduce force output in acute exercises recruiting large muscle groups, which could have adverse implications for training load output. Total load output in a resistance training session (i.e. with a combination of sets, exercises and repetitions) decreased with one night of sleep restriction in athletes.[30] However, the workload performed in multi-joint exercises was restored with caffeine ingestion, compared to no caffeine ingestion.[30] Caffeine is a supplement used to increase physiological alertness and cognitive performance.[6] However, the study by Cook et al.[30] maintained a constant exercise intensity, therefore caffeine may also be valuable in offsetting rising perceived exertion and falling motivation caused by sleep restriction.[30] Countering a diminished motivation to train from sleep-related fatigue, could be particularly valuable for all groups facing inadequate sleep, as a low motivation to train could be an equally large threat to preserving muscle mass as a reduction in training workload itself.

To compound the effect of inadequate sleep, the time of day that resistance exercise is performed may impact muscle strength, due to circadian oscillations or the prolonged amount of prior wake time (e.g. due to advanced waking and/or a night shift). One study reported a strength deficit following a single night of sleep restriction, when athletes were woken early and tested in the evening.[25] In fully rested people, the evening may present an optimal hormonal and metabolic environment in the muscle to maximise resistance exercise adaptations.[43] Therefore, the findings by Soussi et al.[25] may result from a shift in the circadian release of hormones that regulate muscle metabolism and suggest that morning training may be more effective for advanced waking groups. Baseline cortisol is elevated and both baseline and post-resistance training testosterone levels are lowered with a night of sleep restriction.[30] Over multiple nights of sleep restriction alone, anabolic hormone circulation is reduced by up to 15%,[44] which may negatively impact adaptations to resistance training. A longer prior wake time may also reduce central drive.[45] Therefore, cognitive impairments that increase perceived exertion and decrease motivation for executing maximal force may also be important to consider when prescribing training. Napping has been identified as an appropriate and feasible approach to supplement an inadequate main sleep period and restore cognitive alertness, in shiftworkers and older adults.[46] A day time nap following sleep restriction had no effect on grip strength.[29] However, since only an acute isolated strength variable was tested,[29] napping may remain beneficial prior to performing resistance training with compound exercises that require greater cognitive alertness. Collectively, the findings may be important for sleep-restricted groups who may perform resistance training more effectively with caffeine ingestion or following a nap; or prior to prolonged waking periods.

4.2. Muscle strength and hormonal responses to sleep deprivation

Blumert et al.[36] conducted a resistance training session after a night of sleep deprivation. The session consisted of Olympic-style lifts performed by experienced, national calibre weightlifters, tested in groups. No change was found in training capacity or testosterone and cortisol response, suggesting that inadequate sleep does not disrupt the performance or hormonal response to resistance exercise. The findings conflict those of Cook et al.[30] (see Section 4.1) but given similar timing of sampling with respect to the training session and time of day, it is difficult to explain the apparent differences. Blumert et al.[36] suggest that being appropriately motivated may negate the effect of acute sleep deprivation on performance. Social facilitation induced by group training is likely to increase motivation[47] and may be an ideal approach for maintaining strength during training. Given the complexity of the lifts and the training experience of the participants, it is difficult to generalise the findings of Blumert et al.[36] to non-athlete populations, experiencing inadequate sleep and performing moderate forms of resistance training. However, training in groups is likely to be beneficial for less experienced trainers,[47] such as younger athletes, new parents, older adults and shiftworkers. The remaining studies also suggest that a night of sleep deprivation may be insufficient to elicit a deficit in MVC strength[33–35,37] or change in cortisol profile.[34] However, following one night of sleep deprivation and then a recovery sleep, back strength decreased compared to two nights of normal sleep. The findings may be applicable to groups who train after a recovery sleep, such as new parents or shiftworkers who work 24-h shifts (e.g. military services or some fire departments[48]). Perhaps more importantly, the findings highlight the need for all groups to employ training motivation strategies, even after a recovery sleep. Muscle strength and hormonal responses may be maintained following one night of sleep deprivation; however, this may be dependent on the type of resistance exercise, training status and training environment.

Studies implementing sleep deprivation alongside continuous exercise protocols reported mixed results for muscle strength.[38–40] One study found that more strength variables decreased with exercise than with sleep deprivation alone,[39] suggesting that exhaustive exercise may exaggerate the negative relationship between sleep deprivation and resistance exercise. This knowledge is critical for exercise professionals to ensure that exhaustive training is not planned around periods when their recreational clients or professional athletes may be sleep deprived. While this type of extended sleep deprivation with intense physical work may be applicable to military personnel and some physically demanding occupations, it is less translatable to other groups facing inadequate sleep who may not perform physically demanding tasks outside of their resistance training.

4.3. Limitations

The time spent in sleep is important to quantify accurately. Only three studies[27,28,32] in the current review used actigraphy or polysomnography to assess sleep duration prior to or during the intervention. While sleep diaries correlate well with sleep timing and duration, they are not as valid as actigraphy monitors in assessing sleep to wake transitions, nor polysomnography, which remains the gold standard.[49] Several studies were also limited by their statistical analysis, whereby only statistical significance was reported, with no acknowledgement of effect sizes or statistical power. The magnitude of effect that inadequate sleep has on resistance exercise and muscle health is essential to determining the real-world importance of the relationship between these variables.[50] The quality of the studies in the current review were mostly evaluated as 'moderate' with four studies assigned a 'weak' global score. It is important to note that participant blinding cannot be controlled for in sleep deprivation or restriction studies, therefore none of the studies were able to achieve 'strong' global scores. Studies that received a 'weak' global score also typically scored poorly in the domains of selection bias, study design or confounding variables. Implementing a rigorous design is important to ensure that appropriate conclusions are made for individuals experiencing inadequate sleep. Finally, the findings from this review are limited by a lack of shiftworker studies and by a small sample of athlete studies that have mostly implemented severe sleep restriction (3 h) or sleep deprivation (>60 h) periods. Therefore, the reader should consider these limitations regarding the practical application of the findings.

4.4. Future directions

Only four of the reviewed studies included female participants, and only one of these analysed sex differences. The circadian regulation of hormones in women is largely dependent on menstrual cycle phase.[51] Disrupted circadian rhythms, which may occur with inadequate sleep, are associated with menstrual disturbances.[51] Precisely how circadian rhythms, menstrual disturbances, inadequate sleep and skeletal muscle metabolism interact is unknown and warrants the inclusion of women in future studies.

No studies in the current review investigated the direct effect of resistance exercise on skeletal muscle adaptation with inadequate sleep. Nevertheless, authors have hypothesised mechanisms whereby inadequate sleep may dampen anabolic hormones and signalling molecules, consequently down-regulating skeletal muscle protein turnover and growth.[17,18] Recent rodent studies support these hypotheses. Sleep deprivation induced a decline in testosterone, IGF-1 and skeletal muscle mass in male Wistar rats.[52,53] Sleep deprivation also elevated the levels of ubiquitinated proteins, which are markers of protein degradation, in rodents.[52,53] While research in humans is warranted, animal models may provide novel insights into our understanding of the musculoskeletal health problems that may be associated with inadequate sleep.[2] Interestingly, rodents who were subjected to an eight-week resistance training protocol prior to sleep deprivation suffered fewer adverse consequences compared to untrained rats.[52,53] Resistance training may therefore have a protective effect against the increase in catabolism induced by sleep deprivation.[54] The findings compel future investigations into the value of resistance training for preserving the health of sleep-deprived populations. Specifically, further research should examine resistance training and skeletal muscle health with moderate sleep restriction (5–6 h) that more accurately reflects the experience of populations battling inadequate sleep.

5. Conclusions

The current review suggests that sleep deprivation or sleep restriction can impair acute maximal muscle strength in compound movements, when motivation is not facilitated. However, the findings regarding the testosterone-cortisol response to resistance training remain mixed, with further research required to affirm changes associated with inadequate sleep. Importantly, this review is limited by only one study of consecutive nights of sleep restriction existing and only two studies implementing a resistance training session. Regular and structured resistance training sessions, rather than singular testing bouts, are important for skeletal muscle adaptation. Therefore, the interaction between inadequate sleep and resistance training should be the focus of future work.

The limited research makes it difficult to provide evidence-based resistance training recommendations for groups experiencing inadequate sleep. However, based on the reviewed evidence, tentative suggestions can be made. Populations who experience sleep deprivation or sleep restriction may want to perform resistance training in groups to maintain motivation and sustain a manageable lifting intensity that will provide an adequate mechanical stimulus to the muscle. Additionally, to reduce the multiple adverse effects of sleep-related fatigue (e.g., elevated perceived exertion, reduced concentration and alertness), these groups should endeavour to train with prior ingestion of caffeine or before waking time extends considerably. Napping or caffeine ingestion prior to training may improve cognitive function and preserve lifting performance in compound movements requiring increased alertness. While the evening presents an optimal hormonal milieu for resistance training in non-sleep fatigued people,[43] the morning may be an appropriate time for sleep-restricted groups to train if wake time is short and motivation is high; this is dependent on training and working schedules and requires further research. Finally, future studies should prioritise quantifying the interaction of inadequate sleep and resistance training on markers of skeletal muscle metabolism. These investigations will underpin the development of appropriate guidelines for resistance training with inadequate sleep.

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