Title: The effects of sleep loss on military physical performance

Journal: Sports Medicine

Submission Type: Review

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Running head: Sleep and military performance

Abstract word count: 230

Text only word count: 6112

References: 67

Number of Figures: 1

Number of Tables: 6

Conflicts of interest: The authors declare that there are no conflicts of interest.

Key Points

Sleep loss appears to negatively affect aerobic capacity, upper body anaerobic capacity, muscular endurance and military task performance.

Confounding factors such as motivation and nutrition may negate the negative effects of sleep loss on physical domains (e.g. lower body strength and aerobic capacity, respectively).

Because the exact relationship between sleep loss and physical performance in military populations remains unclear, applicable practical recommendations cannot be provided.

Abstract

As part of both training and active service, military members can be exposed to prolonged periods of sleep loss. Given the extent of physical and cognitive performances viewed as critical to successful military performance, such sleep disruption may present risk to health and performance. The primary aim of this narrative review was to investigate evidence on the effect of inadequate sleep on measures of aerobic capacity, anaerobic capacity, muscular strength and muscular endurance in military personnel. Sleep loss appears to have the greatest negative impact on aerobic capacity, muscular endurance and military-specific performance in military populations. The findings showed varied results for handgrip strength and anaerobic capacity, with sleep loss inducing a decrease in mean power of the upper body. In comparison to other measures of performance, lower body muscular strength appeared to be resilient to sleep restriction. However, due to the limited evidence and inter-individual variability in results there is no clear consensus on the specific volume of sleep loss that induces significant or meaningful performance decrements. The difficulties of conducting well designed and controlled interventions in military populations are appreciated. However, due to the low quality of reporting and lack of control for confounders (i.e. physical activity, load carriage, prior sleep debt, motivation and energy intake) in the majority of studies it is difficult to establish the relationship between sleep loss and physical performance in military populations.

1 Introduction

Inadequate or 'poor' sleep has been defined as sustained wakefulness, less than 7 h sleep per night for healthy adults, high frequency of wake after sleep onset and/or irregular sleep patterns [1]. Employees at risk of inadequate sleep include those subjected to shift work (i.e. firefighters [2]), professional athletes (i.e. those travelling across different time zones [3]) and military soldiers (i.e. sustained wakefulness during warfare and field-based training exercises [4]). Sleep conditions in military forces may have the most consequential ramifications where physical and cognitive processes are used to enact decisions in situations which can impact on life and death. This population is commonly exposed to early wake times prior to 0600, prolonged wakefulness (i.e. sleep deprivation of >24 h, a common occurrence for soldiers during warfare) or irregular sleep patterns (i.e. sleep restriction of 3-4 h of sleep per night, during training and combat scenarios) and sustained physical and cognitive stressors during training and/or on the battle field [5]. These demands can result in the onset of sleep-related fatigue, which in turn can induce decreases in alertness and performance outcomes and lead to risks to personal safety or operational problems [6]. As such, this has led to a call from academics, military organisational personnel and industry advisors alike for an increased research focus on sleep in military contexts [7].

The military occupation consists of a unique set of necessary physiological and psychological demands primarily linked to achieving mission objectives whilst avoiding casualties [8]. Many military objectives require a high level of sustained physical function and resiliency, muscular strength and power, and aerobic capacity to collectively meet the demands of the occupation [9]. For instance, muscular strength and anaerobic power are required for the optimal performance of routine tasks such as heavy load carriage, sprinting under load or conducting a casualty drag [10]. Many military tasks also require soldiers to sustain repeated actions over extended periods of time such as manual material handling (MMH) and manoeuvring of loads under conditions of restricted or total absence of sleep during combat exercise [10]. Of concern, there are a variety of indices considered critical to military performance e.g. muscular strength [11], power and aerobic capacity [12], which have been shown to be susceptible to sleep loss [13]. In addition, sleep is a potential mediator of injury risk [14], illness/infection occurrence [15-17] and long-term health outcomes [15]. Furthermore, disruption of soldiers' natural circadian rhythms is associated with number of prior deployments, total number of months in a combat zone as well as self-reported increases in accidents and errors made during missions [18]. Collectively, soldiers risk reductions in work output following extensive combat or training with concurrent sleep loss [19]. Despite this evidence of the effects of sleep loss on constructs of military performance, our understanding of the influence of sleep loss on the physical performance of occupationally relevant tasks within the military remains limited [7]. This is likely due to the difficulty in conducting experiments in military populations, given intellectual property and protection privacy considerations, issues with replicating the field of battle in training and the complexity of defining and quantifying military performance.

Of further concern for military personnel, the effectiveness of military physical training has recently come under question [12, 20]. For instance, 40 to 60 % of military recruits present with a musculoskeletal injury during the initial 8 to 12 weeks of basic military training [21-24]. Such disparity between training and job capacity places a health and financial burden on the organisation and individual. For example, the annual cost of rehabilitation, lost days of work, salary and compensation is estimated to equate to ~$12 billion dollars in the U.S military alone [25]. Collating an understanding of sleep's interaction with performance during aspects of military training or field operations may help identify different mediators of performance, as well as injury risk reduction, safety mitigation and improved health outcomes.

Whilst the effects of sleep loss on physical performance in other domains have been well established i.e. athletes [13, 26] and shift workers [27, 28], there is little known of this relationship in a military context. Recent reviews in military populations have also examined how to manage sleep and alertness [29] as well as various sleep disorders such as insomnia and obstructive sleep apnoea [5], but there remains no peer-reviewed resource which has assessed previous evidence of the effect of sleep loss on various physical aspects of military performance. Therefore, the primary aim of this review is to investigate the impact of inadequate sleep on measures of aerobic capacity, anaerobic capacity, muscular strength and muscular endurance in military personnel.

2 Methods

2.1 Search strategy

This review is narrative or scoping by necessity and definition, rather than systematic or meta-analytical. For instance, there is a lack of studies within the military literature directly focussed on the effects of sleep loss on military physical performance and controlled experiments, thus limiting appropriate methods for statistical combination of results and adequate assessment for a meta-analysis. Since we are unable to systematically assess the methodological quality of included trials, this would not be suitable for such a review [30]. In addition, there is a scarcity of peer-reviewed literature of sufficient quality and evasion of bias. Furthermore, there is insufficient literature with explicit statements surrounding the derivation of their relevant study aims, nor any appropriately randomised groups in these studies. Collectively, such a collection of literature would not satisfy the Assessing the Methodological Quality of Systematic Reviews (AMSTAR) regulations for adequate assessment of methodological quality of a systematic review [31]. There are various reasons for this dearth of sufficient military sleep and performance literature including case study design necessity due to cohort restrictions, data privacy issues, difficulty in instigating control groups in elite armed forces, balancing internal and external validity and the impossibility of replicating the field of battle in training sessions/studies.

2.2 Literature extraction and eligible studies

In order to accomplish this review, a computerized literature search was performed over 10 months (May 2018–March 2019) on MEDLINE/PubMed, Scopus and Web of Science to identify relevant English-language studies published between January 1960 and October 2018. Keywords used in different combinations were ‘sleep’, ‘rest’, ‘deprivation’, ‘loss’, ‘restriction’, ‘army’, ‘defence’, ‘soldier’, ‘military’, ‘armed forces’, ‘navy’, ‘air force’, ‘combat’, ‘exercise’, ‘physical’, ‘physiological’, ‘strength’, ‘power’, ‘muscle’, ‘aerobic’, ‘anaerobic’, ‘work’, ‘performance’, ‘recovery’. Articles were sourced manually from the reference lists of original manuscripts, and previous narrative, systematic, and meta-analytical reviews. Articles were then excluded unless they fulfilled the following criteria: complete (sleep deprivation; SD) or partial sleep deprivation (sleep restriction; SR; at least 2 h of disruption) was incurred for at least one night, participants were active, trainee or recruits within a military population, at least one physical performance measure was collected following sleep loss and trials were performed in the field rather than in the laboratory. Psychomotor or cognitive performance tests (i.e. vigilance, precision, reaction time, memory, attention and coordination) were not eligible for inclusion. Furthermore, studies were not eligible for inclusion where participants underwent sleep loss with concurrent calorie restriction. Calorie restriction may exacerbate the effects of sleep loss on physical performance and therefore should be studied separately. Interventions where participants were purposefully underfed were included only if compared to a moderate- or high-calorie intake group. Articles were then screened for duplicates and removed if necessary (Figure 1). Following this literature search, 15 articles were extracted for the focus of this review (Tables 1-6).

3 Results and Discussion

3.1 Sleep Loss and Aerobic Performance

Many military tasks require sustained physical activity, such as road marches, land navigation, manoeuvring obstacles and evacuating casualties over long distances [32]. Individuals with the ability to maintain aerobic fitness under demanding conditions of sleep loss and prolonged physical activity have a greater capacity to sustain military tasks and optimise combat performance [9]. Previous studies have investigated the effects of sleep loss protocols on aerobic performance in military personnel and revealed similar reductions in aerobic capacity (Table 1). However, these findings are difficult to compare due to varying protocols and the combination of sleep loss with confounding factors including dietary and training interventions. For example, Keramidas et al. [33] examined the effects of SR on a 3-km run test in 61 male and female cadets. After the completion of the trial subjects were randomly allocated to either a control (without a pre-exercise nap) or a nap (with a 30 min pre-exercise nap) group. The authors reported that 3 km running performance was significantly impaired in the control group. However, performance remained unaltered in subjects who were permitted an additional 30 min nap prior to testing. These findings suggest that a pre-exercise nap may attenuate the negative effects that sleep loss has on aerobic performance. Similarly, Knapik et al. [34] reported that the time taken to complete a 2-mile run test slowed significantly (14.4±1.7 to 15.6±1.9 min) following a SR protocol of 5 h sleep per night for 5 nights. However, the 2-mile run test was conducted immediately following a battery of muscular endurance testing as part of the Army Physical Fitness Test which would have likely affected the results.

More recently, some studies have investigated the effect of sleep loss on both the performance and physiological responses to aerobic exercises. For example, Tomczak et al. [35] examined the heart rate (HR) response and time to completion of a 1-mile walk test following 36 h of SD combined with moderate physical activity in air force cadets. Despite no significant change in the time to completion of the 1-mile walk test, HR at completion was significantly lower following the SD protocol (148±6 to 132±3 bpm). Similarly, Vaara et al. [36] reported no change in the maximal aerobic performance of cadets during a progressive cycle ergometer test following a 60 h SD protocol. However, only half of the participants (i.e. 10 participants) from the trial were selected to complete the aerobic performance testing. The authors reported a decrease in maximal blood lactate (10.7±2.2 to 8.2±2.4 mmol/L) as well as a decrease in submaximal (100-250 W) HR, oxygen consumption (VO_2) and ventilation. These altered submaximal cardiorespiratory responses were not replicated at maximal levels, with no reported change in maximal HR, VO_2, ventilation or respiratory exchange ratio. The authors attributed these changes in physiological responses to possible alterations in glycogen metabolism and metabolic rate that occur as a result of SD. Keramidas et al. [37] reported alterations in aerobic capacity and cardiorespiratory responses during high-intensity constant-load cycling following a 51 h trial where participants attained a total of 5 h sleep. Participants performed two constant-load trials, one trial at 65% and another at 85% of their peak power output (PPO). The findings showed a 29% reduction in time to exhaustion at 85% of PPO; however, performance was not affected at 65% of PPO. The authors reported significant decreases in blood lactate and respiratory exchange ratio during both constant-load trials. Increases in submaximal VO_2 and HR at 65% of PPO were also observed. The authors suggested that these results may indicate a reduction in whole-body mechanical efficiency or a decrease in liver and skeletal muscle glycogen. Collectively, these results show performance impairments and physiological alterations in submaximal aerobic performance, whereas maximal aerobic performance appears to remain relatively unaffected. These findings are in accordance with previous research performed in other populations such as athletes and firefighters [13, 38]. These reports have shown that although performance of submaximal physical tasks declines significantly with sleep loss, maximal physiological function is not unduly compromised [13, 38].

Previous studies have also investigated the effects of sleep loss in combination with different energy intakes on aerobic performance. For example, Guezennec et al. [39] implemented 3-4 h of SR per day combined with a low-calorie intake of 1800 kcal/24 h for 5 consecutive days of combat training. The estimated energy expenditure of the combat training was approximately 5000 kcal/24 h. The authors reported a 14% decrease in power output (325 to 278 W) at exhaustion and an 8% decrease in maximal oxygen uptake (VO_{2max}) (3.74 to 3.45 $l \cdot min^{-1}$) following an incremental cycle test. These findings were not replicated for participants performing the same sleep and training protocol whilst receiving either moderate- or high-calorie intakes (3200 and 4200 kcal/24 h, respectively). The authors attributed the decline in aerobic performance to the severe energy deficit, resulting in a decrease in blood glucose availability and an increase in fat oxidation. In contrast to these findings, Rognum et al. [40] found no significant change in aerobic performance between low- or high-calorie intake groups (1500 and 8000 kcal/24 h, respectively) undertaking a SD protocol of <2 h sleep over 107 h. However, the authors did not report changes from baseline aerobic performance, but rather compared groups following the completion of the SD protocol. Whilst it is evident that energy intake influences physical performance during sleep loss, it remains unclear whether the effects of sleep loss are greater than those of energy restriction. Collectively, these results show that sleep loss protocols impair the aerobic capacity of soldiers during simulated combat. These are expected findings given that SD exacerbates slowed glycogen resynthesis [41]. However, the observed reduction in aerobic capacity may have been due to the independent effect of manipulating energy intake or the effect of fatigue from prior testing or training. More research is required controlling for these variables before a greater understanding of sleep loss and aerobic capacity in military personnel can be obtained.

INSERT TABLE 1 ABOUT HERE

3.2 Sleep Loss and Upper Body Anaerobic Capacity

The ability to maintain anaerobic power whilst engaging in demanding physical activity under conditions of restricted or deprived sleep is critical to the effectiveness of soldiers. Previous studies have examined the effects of sleep loss interventions on upper body anaerobic capacity and found varied results (Table 2). For example, Murphy et al. [42] reported that mean anaerobic power was significantly impaired (416.6±73.9 to 397.2±59.7 W) following 4-5 h sleep per day for 5 consecutive days of simulated military combat. Similarly, Knapik et al. [34] reported a decrease in mean power output following a comparable SR intervention of 5 h sleep per day for 5 days. The subjects in these previous studies undertook simulated combat exercise during the intervention involving constant load carriages of 27±2 and 28.1 kg, respectively [34, 42]. Collectively, these authors attributed the decrements in mean upper body anaerobic capacity to the confounding factors of SR and muscular fatigue from the loads carried. However, comparisons were not made to participants who undertook equivalent training interventions with adequate sleep. Similarly, Legg and Patton [43] investigated the physiological effects of sustained SR of 3-4 h per night (SR only) or SR combined with MMH of a 58 kg load (SR+MMH). A significant decline in mean power output (4.5±0.5 to 4.2±0.4 W) during the Wingate test was reported only for the SR+MMH group. The authors attributed the decline in mean upper body anaerobic power to the sustained MMH. Collectively, these findings suggest that SR negatively affects upper body anaerobic capacity; however, it appears that the potential muscular fatigue induced by the loads carried may have a greater impact on the decline observed in upper body anaerobic capacity during periods of sleep loss. Murphy et al. [42] proposed that due to military training practices the upper body muscles are not well conditioned with respect to load demand during sustained operations and thus are susceptible to performance decrements. The authors suggested a revaluation of military training practices to include additional upper body conditioning.

The findings of these previous studies are in contrast to those of Patton et al. [44] who observed no reductions in upper body anaerobic capacity following an 8-day simulated combat scenario with a SR protocol of 5.3 h sleep per day. These findings may be attributed to the modest SR and military tasks undertaken throughout the trial. However, as the authors reported no inter-subject variation the exact relationship between sleep loss and upper body anaerobic capacity remains unclear. Reductions in mean anaerobic capacity were reported in previous studies that implemented a significantly higher degree of upper body exercise in the form of load carriage or MMH and averaged less sleep per day [34, 42, 43]. These observed reductions have been attributed to an increased perception of effort or reduced motivation [43]. Collectively, these findings suggest that upper body peak power is not influenced by sleep loss. However, upper body mean power output may be negatively affected following sustained sleep loss (i.e. ≤ 3-5 h SR/24h) with concurrent load bearing activities. A previous study has suggested that decrements in performance during sleep loss with underfeeding and prolonged military work are primarily restricted to tasks that recruit muscles that are over-utilised without adequate recovery [19]. However, to our knowledge, no studies have compared the effects of sleep loss and load carriage with sleep loss alone on anaerobic capacity. Further research accounting for confounding factors (i.e. physical activity and load) is required to accurately determine the interaction between sleep loss and upper body anaerobic capacity in military populations.

INSERT TABLE 2 ABOUT HERE

3.3 Sleep Loss and Lower Body Anaerobic Capacity

Preservation of lower body anaerobic capacity throughout periods of unavoidable sleep loss is particularly important for the occupational tasks required of military personnel. Soldiers often require lower body anaerobic power to rapidly manoeuvre heavy loads in combat and training [9]. The effect of sleep loss on lower body anaerobic capacity has previously been examined in military personnel using a variety of SR and SD protocols with conflicting results (Table 3). For example, Murphy et al. [42] employed a SR protocol of 5 h sleep per day over 5 days of sustained combat exercise. The authors reported increases in peak power reported with no significant change in mean power. The magnitude of change was not provided. Additionally, this study did not include test familiarisation, thereby potentially inhibiting maximal pre-trial performance. Similarly, Knapik et al. [34] reported a significant increase in peak power with no significant change in mean power following a similar SR protocol of 4-5 h sleep per day over 5 days. These findings were attributed to the learning effect and training influences of performing an unfamiliar task.

In contrast to the previous findings, studies have reported increases in lower body mean and peak anaerobic power of the lower body. For example, Legg and Patton [43] investigated the effect of a sustained SR protocol of 3-4 h per day with concurrent MMH on anaerobic capacity. During this investigation participants were grouped into SR only and SR+MMH. The authors reported significant increases in all indices of lower body anaerobic power following the 8 day protocol for both the SR only (peak power: 7.7±0.9 to 8.9±0.5 W, mean power: 6.0±1.0 to 6.9±0.4 W) and the SR+MMH groups (peak power: 7.5±0.9 to 8.7±1.0 W, mean power: 5.8±0.8 to 6.7±0.8 W). The authors attributed these findings to a training effect resulting from the high level of physical activity and military exercise undertaken during the intervention. Additionally, Guezennec et al. [39] reported no significant difference in the time spent at maximal load on a cycle ergometer following 3-4 h of SR for 5 days of simulated combat exercise. Collectively, these previous studies suggest that anaerobic performance is not affected by sleep loss.

More recently, studies have reported that SD negatively impacts lower body anaerobic performance. For example, Tomczak [45] found decrements in the performance of a battery of maximal sprint tests in military pilots following 36 h of SD. The author reported significant decreases in the 15 m sprint (5.01±0.43 to 4.64±0.51 m/s) and the 15 m squat sprint tests (2.20±0.60 to 1.98±0.46 m/s). More recently, the author implemented the same SD protocol in air force cadets and reported similar findings validating the previous results [35]. The authors reported a reduction in the 15 m sprint performance (4.84±0.2 to 4.71±0.3 m/s) following the 36 h SD protocol. A recovery of 7-8 h sleep resulted in a further decrease in sprint performance (4.63±0.2 m/s). This finding suggests that following prolonged SD and military exercise, a longer recovery period (i.e. >7-8 h) is required to restore lower body anaerobic capacity. However, it is questionable whether sprint performance is relevant for pilots or members of the air force. There appears to be no clear consensus on the effects of SR or SD on lower body anaerobic performance. Further research with the inclusion of testing familiarisation sessions and controlling for confounding factors (i.e. physical activity and load carriage) is required to gain a greater understanding of the interaction between sleep loss and lower body anaerobic performance in military personnel, especially with regards to the relevant tasks they regularly perform.

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3.4 Sleep Loss and Muscular Strength

Muscular strength is required for the optimal performance of routine tasks such as heavy load carriage, sprinting under load or conducting a casualty drag [10]. For instance, handgrip strength has been established as a predictor of success in direct combat and throwing which may translate to improved military performance particularly in the evacuation of casualties and manoeuvring of heavy loads [46]. Furthermore, finger dexterity and manual dexterity have been shown to be important for manipulative skills such as operating, positioning and aiming weaponry [47]. As such, strength is becoming increasingly recognised as an essential component of military fitness due to its translation to improved performance on the battlefield [10]. Accordingly, the maintenance of muscular strength under conditions of partial or total sleep loss is required for effectiveness during military combat [10].

The primary test used to measure the impact of sleep loss on muscular strength in this review is the measurement of handgrip strength (Table 4). However, the application of this test is restricted to upper extremity strength and is not reflective of whole-body muscular strength. Handgrip force is further limited in a military context as it is significantly affected by short term nutritional deprivation [48]. Two out of eight studies testing handgrip performance reported a consistent decrease in muscle strength with no apparent restoration throughout the trial. For example, Tomczak [45] measured muscular strength through handgrip strength following 36 h of SD combined with physical activity in military pilots. Significant decreases in maximal handgrip strength (672±268 to 630±249 N) and indices of force differentiation were reported. Similarly, Legg and Patton [43] found that isometric handgrip strength progressively declined over 8 days of sustained manual work with 3-4 h of sleep per night. These results were consistent with other investigations that reported impairments in maximum handgrip strength following SD protocols [49]. The observed decline in handgrip strength has been attributed to either a decrement in muscle fibre recruitment or an alteration in motor unit firing frequency following SD [43]. No restoration in handgrip strength was reported following a 7-8 h sleep recovery period [35] or over 3 post-trial recovery days [43]. These findings suggest that a reduction in muscle strength may persist for a prolonged period following sustained sleep loss and military exercise.

Previous studies have demonstrated increases in indices of upper body muscular strength following sleep loss protocols. For example, Patton et al. [44] reported improvements in isometric handgrip strength (62.7±7.8 to 66.9±10.5 kg) and isokinetic elbow flexor strength (30°/s: 55.3±10.0 to 62.1±12.2 Nm, and 180°/s: 41.5±8.5 to 48.7±11.7 Nm) following a SR protocol of 8 days with 5.3 h sleep per day. Similarly, Knapik et al. [34] demonstrated increases in handgrip strength following 5 h sleep per day for 5 days. These findings have been attributed to a possible learning effect due to neuromuscular adaptation or an end spurt effect due to an increase in soldier morale and motivation as a result of successfully completing the trial [34]. However, these findings may also be attributed to the modest SR protocols implemented (i.e. 5.3 and 5 h). Several studies in healthy populations have shown that handgrip strength is maintained regardless of sleep loss protocol [13, 50]. However, further research with a variety of sleep loss interventions is required before a consensus can be reached on the effects of sleep loss on muscular strength in military populations.

In contrast to the previous findings, studies have reported that muscular strength fluctuates over time as a representation of the circadian rhythm. For example, Goh et al. [51] found handgrip strength variations regardless of sleep condition (i.e. adequate sleep or total SD) over 24 h. The authors observed a progressive increase in handgrip strength until 6 pm followed by a steady decline throughout the night. These findings suggest that muscular strength is not influenced by SD. Similarly, How et al. [52] reported a decline in handgrip strength over 0-42 h SD, followed by an apparent recovery between 42-72 h SD, and a rapid deterioration in strength from 72-102 h SD. However, participants were progressively withdrawn from the trial once they could no longer stay awake. Similarly, Foo et al. [49] demonstrated fluctuations in handgrip strength throughout a SD trial in navy seamen. The authors reported a progressive decline from 0-48 h SD, followed by an improvement in strength between 48-66 h SD. The apparent recovery of handgrip strength may be attributed to an adaptation to the effects of fatigue induced by SD that stabilises or counteracts the effects of sleep loss. The effect of circadian phase on muscular strength has been well documented in a laboratory setting under normal sleep conditions [53]. Handgrip strength appears to remain relatively stable across wake periods with highest values occurring around the evening [53]. Further research is required to establish the mechanisms behind the observed fluctuations in handgrip strength and whether muscular strength indeed adopts a circadian profile under conditions of sleep loss in a military context.

Relatively fewer studies have reported on the effects of sleep loss on lower body muscular strength and demonstrated no negative effect. For example, Vaara et al. [36] reported no significant change in maximal isometric knee extension force following a 60 h SD protocol with light physical activity. The findings also revealed no changes in electromyography or rate of force development. Moreover, two studies have reported increases in lower body muscular strength during conditions of sleep loss [34, 44]. Patton et al. [44] reported significant increases in the incremental deadlift (73.4±15.3 to 83.7±16.2 kg) and all indices of isokinetic knee flexor strength *(*30o/s: 212±58 to 249±57 Nm, and 180o/s: 147±35 to 167±37 Nm) following 5.3 h of SR over 8 days. Similarly, Knapik et al. [34] reported a significant increase in dynamic lift strength following 5 days of 5 h sleep per day. No significant change was reported in isokinetic or isometric knee flexor strength. The increase in muscular strength demonstrated was attributed to an end spurt effect due to an increase in motivation and verbal encouragement among participants [34]. Further research with standardised testing procedures that account for motivational components of tasks is required. Given the risks involved in real world scenarios, motivation would presumably be less required for military populations. Nonetheless, team work and leadership are considered essential in a military context where individuals are often required to work together and perform under stressful circumstances [54]. Collectively, previous studies investigating the relationship between sleep loss and muscular strength have demonstrated conflicting findings in military populations. Due to the limitations in the design of these studies findings must be taken with caution.

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3.5 Sleep Loss and Muscular Endurance

The importance of muscular endurance during various military training and combat tasks has previously been established [55]. Indeed, many military tasks require soldiers to sustain repeated actions over extended periods of time. Soldiers are often required to perform monotonous physical handling and manoeuvring of materials under conditions of restricted or total absence of sleep during combat exercise. Accordingly, the ability to maintain muscular endurance under these conditions has been shown to increase efficiency of military tasks and optimise combat effectiveness [55]. To date, a limited number of studies have investigated the interaction between sleep loss and muscular endurance and found a negative response [33, 34, 42] (Table 5). For example, Keramidas et al. [33] examined the effects of SR (5 h sleep obtained over 51 hours of continuous military training) on the maximum number of lunges completed in 2 min. The authors reported no change in the number of repetitions of lunges completed for the control group (without a pre-exercise nap). However, the performance of the nap group (with a 30 min pre-exercise nap) significantly increased following SR. These findings suggest that the 30 min nap may acutely improve muscular endurance following sleep loss. Similarly, Knapik et al. [34] reported the maximum number of sit-ups completed in 2 min and push-ups completed in 2 min and found a significant decline following 5 h of sleep per day for 5 days (66.8±10.7 to 61.6±10.4 and 66.0±12.3 to 59.8±14.9 repetitions, respectively). Significant declines were further reported in knee extensor mean torque and elbow flexor mean and maximum torque in a muscular endurance test involving 50 consecutive maximal contractions. Utilising the same muscular endurance test, Murphy et al. [42] also reported significant declines in knee extensor mean torque (75.4±17.6 to 70.4±17.7 Nm) and elbow flexor maximum torque (37.4±8.8 to 33.6±8.4 Nm) following 4-5 h sleep per day for 5 days. Collectively, these previous studies suggest that sleep loss has a negative effect on muscular endurance. Further studies should seek to elucidate the possible mechanism underlying this negative relationship.

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3.6 Sleep Loss and Military Specific Performance

Sleep loss is an unavoidable occupational characteristic of military service, particularly during deployment and combat training. Although military performance is difficult to define, insufficient sleep has previously been reported as the most influential factor in the effectiveness of military performance [5]. Accordingly, the ability to maintain peak performance of military tasks under conditions of inevitable sleep loss is critical to efficiency and effectiveness of soldiers. Previous studies have shown a consistent negative relationship between sleep loss and military specific task performance [34, 40, 56] (Table 6). For example, Knapik et al. [34] implemented the Army Physical Fitness Test (maximum sit-ups in 2 min, maximum push-ups in 2 min, 2 mile run) and found significant decrements in the test score following 5 h sleep per day for 5 days. Similarly, Rognum et al. [40] reported a decline in the performance of a 1 km assault course following a SD protocol of <2 h sleep obtained over 107 h. No significant differences were observed in the assault course score between subjects who obtained either a low- or high-energy intake (1500 and 8000 kcal/day, respectively). These findings suggest that sleep loss, in comparison to energy restriction, may have a more detrimental effect on physical performance when performing specific military tasks.

Previous studies have also utilised the subjective evaluation of supervising military officers to report on the performance of soldiers under conditions of sleep loss [34, 40, 56]. For example, Knapik et al. [34] found no apparent decrement in military squad performance throughout a 5 day simulated combat trial with 5 h sleep/day. Squad performance was rated by senior infantry officers based on the U.S. Army performance standards. Similarly, Haslam [56] reported that soldiers remained 'effective' for up to 9 days with 3 h sleep, 6 days with 1.5 h sleep and 2 days with no sleep. The author recommended that 4 h sleep per day may be sufficient for restoring and sustaining military effectiveness. Additionally, Rognum et al. [40] reported that military effectiveness progressively declined from 24 h without sleep regardless of energy intake (i.e. 1500 or 8000 kcal/day). Previous research of Patton et al. [44] found that during an 8 day trial with 5.3 h sleep per night the physical task performance of soldiers was significantly impaired on days 2-7. However, performance effectiveness was rated significantly higher on the final day of the trial (day 8). These findings suggest that group morale and high motivation to complete a task may mitigate the negative effects of sleep loss. Collectively, these results suggest that military performance deteriorates under sleep loss conditions. However, motivation may acutely mitigate the negative effects of sleep loss. The declines reported in military effectiveness support the postulation that sleep loss has a major influence on military specific performance. However, caution must be exercised when interpreting these findings due to the subjective nature of the results. Nevertheless, these findings provide practical information for commanding officers regarding soldier deployment duration and recovery time before redeployment in order to maintain the effectiveness of combat. Further research of a controlled randomised design and accounting for confounding factors (i.e. energy intake and physical activity) is required before a greater understanding of the sufficient amount of sleep required for military effectiveness can be obtained.

INSERT TABLE 6 ABOUT HERE

3.7 Additional Considerations

The purpose of this review was to examine the effects of sleep loss on military physical performance. However, it is necessary to consider the effect that sleep loss has on cognitive performance and mood. It is well established that sleep loss degrades cognitive performance [57]. Previous studies in military populations have consistently shown impairments in vigilance, reaction time and working memory [58, 59]. Sleep loss has also shown to decrease motivation and increase perception of effort [60, 61]. However, the exact mechanisms underlying the relationship between sleep and cognition remain unclear. Additional factors influencing performance (i.e. nutrition and occupational demands) that were outside the scope of this review also warrant consideration. Previous studies have shown that underfeeding combined with sleep loss can have significant adverse effects on both cognitive [4, 60] and physical [4, 19] performance during military operations. Cognitive function has also been reported to decline faster than physical performance when nutrition is restricted [4]. Military populations are exposed to severe, multifactorial stressors during warfare that lead to significant degradations in cognitive and physical performance. Interventions to mitigate these negative effects such as appropriate nutrition should be considered when sleep loss is unavoidable.

This review may also have varying implications in different military contexts due to the diversity of military occupational demands. For example, previous studies have investigated the effects of sleep loss on measures such as navigation and self-paced work. These findings show that high-speed navigation and well learned military skills are maintained under conditions of restricted sleep [19, 62]. However, the intensity of self-paced work and self-selected walking pace has been reported to decline with combined sleep loss and physical fatigue [38, 63]. The effects of fatigue countermeasures (i.e. caffeine and stimulants) should also be considered as they may aid military personnel during sustained operations. For example, previous studies have reported that sleep deprived participants, supplemented with caffeine, improved in measures of military specific cognitive performance (i.e. vigilance and marksmanship) and physical performance (i.e. running speed and obstacle course time to completion) [64-66]. Psychostimulants have further been shown to improve performance under conditions of sleep loss [67]. These findings suggest that fatigue countermeasures may attenuate the negative effects of sleep loss and should be considered during military operations where opportunities for sleep are not available.

4 Future Research

Given the potential impact of sleep loss and the effects on physical performance in a military context, it is essential that the research in this area is examined critically. Due to the lack of randomised controlled trials and low quality of reporting in previous studies, further research is required to make practical recommendations regarding sleep duration and physical efficiency in military populations. Future studies should account for confounding factors (i.e. physical activity, load carriage, prior sleep debt and energy intake) and describe the quality and duration of sleep attained by participants in detail. The effect of fatigue countermeasures (e.g. caffeine, stimulants, light interventions, naps and melatonin) on physical performance should be further investigated by authors given their practical significance in military populations. Future investigators should also consider examining the circadian variation in performance during periods of sleep loss. While the difficulties of performing such research in military populations are appreciated, well controlled and reported studies are required to develop a greater understanding of the effects of sleep loss on physical performance.

5 Conclusion

The primary aim of this review was to critically analyse the existing literature to elucidate the effects of sleep loss on physical performance in military populations. Despite the potentially serious implications of physical inefficiency, to date, there is insufficient literature investigating the effects of sleep loss on physical performance in a military context. The previous military-based studies provide an insight into the effects that sleep loss may have on the physical capacities of soldiers. However, caution must be exercised when interpreting these finding due to the lack of randomisation and controlling for results demonstrated in the current literature. Further research controlling for these limitations is required to accurately determine the interaction between sleep loss and physical performance in military populations.

Compliance with Ethical Standards

Funding

No sources of funding were used to assist in the preparation of this article.

Conflicts of Interest

Clementine Grandou, Lee Wallace, Hugh Fullagar, Rob Duffield and Simon Burley declare that they have no conflicts of interest relevant to the content of this review.

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Table 1. Studies examining the effects of sleep loss on aerobic performance

Reference	Participants	Sleep intervention	Military task	Exercise protocol	Performance outcome	Result
Rognum et al. [40]	24 male soldiers	SD: <2 h of sleep obtained over 107 h followed by 6 nights of normal sleep	Heavy sustained work	3-kilometer run	Time (min)	NS
Knapik et al. [34]	34 male infantry soldiers	SR: 5 h of sleep obtained per night for 5 nights	Simulated combat exercise	2-mile run	Time (min)	↓
Guezennec et al. [39]	27 male soldiers	SR: 3-4 h of sleep obtained per night for 5 nights	Simulated combat exercise. Low, moderate & high cal groups	Graded exercise test	Peak power (W)	↓ (low cal) NS (moderate cal) NS (high cal)
Tomczak et al. [35]	15 air force cadets	SD: 36 h	Moderate physical activity and military tasks	1-mile walk	Time (min)	NS
Keramidas et al. [37]	14 male and female cadets	SR: 5 h sleep obtained over a 51 h trial	Continuous military field tasks	Constant-load trial at 65% of peak power output	Time to exhaustion (min)	NS
				Constant-load trial at 85% of peak power output	Time to exhaustion (min)	↓
Keramidas et al. [33]	61 male and female cadets	Control - SR: 5 h sleep obtained over a 51 h trial. Nap - SR: 5 h sleep obtained over a 51 h trial followed by 30 min sleep before performance tests.	Continuous military field tasks	3-kilometer run	Time (min)	↑ (control) NS (nap)
Vaara et al. [36]	20 male cadets	SD: 60 h	Sedentary military tasks and occasional light physical activity	Progressive exercise test	Time to exhaustion (min)	NS

SR, sleep restriction; *SD, sleep deprivation*; *W,* watts; *HR,* heart rate; *bpm,* beats per minute; *min,* minutes; VO_{2max}, maximal oxygen uptake; *cal,* calorie; *NS,* not significant; ↑ and ↓ indicate increase and decrease, respectively.

Table 2. Studies examining the effects of sleep loss on anaerobic capacity of the upper body

References	Participants	Sleep intervention	Military task	Exercise protocol	Performance outcome	Result
Murphy et al. [42]	34 male soldiers	SR: 4-5 h of sleep obtained per night for 5 nights	Simulated combat exercise	Wingate anaerobic test	Peak power (W) Mean power (W)	NS ↓
Legg and Patton [43]	25 male soldiers	SR: 3-4 h of sleep obtained per night for 8 nights	Sustained manual work	Wingate anaerobic test	Peak power (W) Mean power (W)	NS ↓
Patton et al. [44]	24 male soldiers	SR: 5.3 h of sleep obtained per night for 8 nights	Simulated combat exercise	Wingate anaerobic test	Peak power (W) Mean power (W)	NS NS
Knapik et al. [34]	34 male infantry soldiers	SR: 5 h of sleep obtained per night for 5 nights	Simulated combat exercise	Wingate anaerobic test	Peak power (W) Mean power (W)	NS ↓

SR, sleep restriction; *W*, watts; *NS*, not significant; ↓, decrease.

Table 3. Studies examining the effects of sleep loss on anaerobic capacity of the lower body

Reference	Participants	Sleep intervention	Military task	Exercise protocol	Performance outcome	Result
Murphy et al. [42]	34 male soldiers	SR: 4-5 h of sleep obtained per night for 5 nights	Simulated combat exercise	Wingate anaerobic test	Peak power (W) Mean power (W)	↑ NS
Legg and Patton [43]	25 male soldiers	SR: 3-4 h of sleep obtained per night for 8 nights	Sustained manual work	Wingate anaerobic test	Peak power (W) Mean power (W)	↑ ↑
Patton et al. [44]	24 male soldiers	SR: 5.3 h of sleep obtained per night for 8 nights	Simulated combat exercise	Wingate anaerobic test	Peak power (W) Mean power (W)	NS NS
Knapik et al. [34]	34 male infantry soldiers	SR: 5 h of sleep obtained per night for 5 nights	Simulated combat exercise	Wingate anaerobic test	Peak power (W) Mean power (W)	↑ NS
Guezennec et al. [39]	27 male soldiers	SR: 3-4 h of sleep obtained per night for 5 nights	Simulated combat exercise	Cycling test to exhaustion	Time	NS
Tomczak [45]	13 military pilots	SD: 36 h	Survival training	Maximal sprint tests	15-m sprint (m/s) 3x 5-m shuttle run (m/s) 15-m slalom run (m/s) 15-m squat sprint (m/s)	↓ NS NS ↓
Tomczak et al. [35]	15 air force cadets	SD: 36 h	Moderate physical activity and military tasks	Maximal sprint tests	15-m sprint (m/s) 3x 5-m shuttle run (m/s) 15-m slalom run (m/s) 15-m squat sprint (m/s)	↓ NS NS NS

SR, sleep restriction; *SD, sleep deprivation*; *W,* watts; *m/s,* meters per second; *NS,* not significant; ↑ and ↓ indicate increase and decrease, respectively.

Table 4. Studies examining the effects of sleep loss on muscular strength

Reference	Participants	Sleep intervention	Military task	Exercise protocol	Performance outcome	Result
Legg and Patton [43]	25 male soldiers	SR: 3-4 h of sleep obtained per night for 8 nights	Sustained manual work	Muscular strength test	Handgrip test (kg)	↓
Patton et al. [44]	24 male soldiers	SR: 5.3 h of sleep obtained per night for 8 nights	Simulated combat exercise	Muscular strength tests	Isokinetic elbow flexion torque (Nm)	
					30 º/s	↑
					180 º /s	↑
					Isokinetic knee extension torque (Nm)	
					30 º /s	↑
					180 º /s	↑
					Handgrip test (kg)	↑
					Incremental deadlift (kg)	↑
Knapik et al. [34]	34 male infantry soldiers	SR: 5 h of sleep obtained per night for 5 nights	Simulated combat exercise	Muscular strength tests	Isokinetic elbow flexion torque (Nm)	
					3.14 rads	↓
					0.52 rads	↓
					Isokinetic knee extension torque (Nm)	
					3.14 rads	NS
					0.52 rads	↓
					Isometric elbow flexion torque (Nm)	↓
					Isometric knee extension torque (Nm)	NS
					Handgrip test (N)	↑
					Upright pull (N)	NS
					Dynamic lift (N)	↑
Foo et al. [49]	20 male seamen	SD - SR: 42 h SD followed by either 0, 2 or 4 h of sleep for 1 night	Light activity	Muscular strength test	Handgrip test (N)	↓
How et al. [52]	20 male seamen	SD: for up to 102 h	Light activity	Muscular strength tests	Handgrip test (N)	↓
Goh et al. [51]	14 military service members	SD: whole night	Light activity	Muscular strength tests	Handgrip test (N)	↓
Tomczak [45]	13 military pilots	SD: 36 h	Survival training	Muscular strength tests	Handgrip test (N)	
					Max force	↓
					50% max	↓
					Corrected 50% max	↓
Tomczak et al. [35]	15 air force cadets	SD: 36 h	Moderate physical activity and military tasks	Muscular strength tests	Handgrip test (N)	
					Max force	↓
					50% max	NS
					Corrected 50% max	↓
Vaara et al. [36]	20 male cadets	SD: 60 h	Sedentary military tasks and occasional light physical activity	Muscular strength test	Max isometric knee extension force (N)	NS

SR, sleep restriction; *SD, sleep deprivation*; *Nm*, newton meters; *rads*, radians; *max*, maximum; *N*, newtons; *kg*, kilograms; *º /s*, degrees per second; *NS*, not significant; ↑ and ↓ indicate increase and decrease, respectively.

Table 5. Studies examining the effects of sleep loss on muscular endurance

Reference	Participants	Sleep intervention	Military task	Exercise protocol	Performance outcome	Result
Murphy et al. [42]	34 male soldiers	SR: 4-5 h of sleep obtained per night for 5 nights	Simulated combat exercise	Thorstensson test	Elbow flexion	
					Max peak torque (Nm)	↓
					Avg peak torque (Nm)	NS
					Knee extension	
					Max peak torque (Nm)	NS
					Avg peak torque (Nm)	↓
Knapik et al. [34]	34 male infantry soldiers	SR: 5 h of sleep obtained per night for 5 nights	Simulated combat exercise	Muscular endurance tests	Sit-ups (reps)	↓
					Push-ups (reps)	↓
				Thorstensson test	Elbow flexion	
					Max peak torque (Nm)	↓
					Avg peak torque (Nm)	↓
					Knee extension	
					Max peak torque (Nm)	NS
					Avg peak torque (Nm)	↓
Keramidas et al. [33]	61 cadets	Control - SR: 5 h sleep obtained over a 51 h trial. Nap - SR: 5 h sleep obtained over a 51 h trial followed by a 30 min nap before performance tests.	Continuous military field tasks	Muscular endurance test	Lunges (reps)	NS (control) ↑ (nap)

SR, sleep restriction; *reps*, repetitions; *max*, maximum; *avg*, average; *Nm*, newton meters; *NS*, not significant; ↑ and ↓ indicate increase and decrease, respectively.

Table 6. Studies examining the effects of sleep loss on military specific performance

Reference	Participants	Sleep intervention	Military task	Exercise protocol	Performance outcome	Result
Haslam [56]	68 infantry soldiers	SR: 1.5 or 3 h of sleep obtained per night for 9 nights	N/A	Military tasks	Military effectiveness	↓
Rognum et al. [40]	24 male soldiers	SD: <2 h of sleep obtained over 107 h followed by 6 nights of normal sleep	Heavy sustained work	Military tasks	Military effectiveness Assault course (min)	↓ ↓
Patton et al. [44]	24 male soldiers	SR: 5.3 h of sleep obtained per night for 8 nights	Simulated combat exercise	Military tasks	Physical performance evaluation	↓ (day 2-7) ↑ (day 8)
Knapik et al. [34]	34 male infantry soldiers	SR: 5 h of sleep obtained per night for 5 nights	Simulated combat exercise	APFT Military tasks	Sit-ups + push-ups + 2-mile run Squad performance score	↓ NS

SR, sleep restriction; *SD, sleep deprivation*; *APFT,* Army Physical Fitness Test; *min,* minutes; *N/A,* not available; *NS,* not significant; ↑ and ↓ indicate increase and decrease, respectively.