Sports Medicine
https://doi.org/10.1007/s40279-026-02555-9

REVIEW ARTICLE

Post-Exercise Thermal Interventions and Nocturnal Sleep in Athletes: A Narrative Review of the Potential Underlying Physiological Mechanisms

Panagiotis G. Miliotis[1] · Shona L. Halson[2,3] · Toby Mundel[4] · Josh Leota[5,6,7] · Argyris G. Toubekis[1,8] · Petros G. Botonis[1,8]

Accepted: 25 September 2026
© The Author(s), under exclusive licence to Springer Nature Switzerland AG 2026

Abstract

Sleep is essential for optimal performance and recovery in athletes. Post-exercise cold exposure, including cold water immersion and cryotherapy, is typically used to enhance recovery, but its effects on sleep remain unclear. Emerging evidence also suggests that post-exercise heat exposure, including sauna and hot water immersion before sleep may improve both objective and subjective sleep outcomes. However, the effectiveness of post-exercise thermal interventions for improving nocturnal sleep in athletes specifically has not yet been comprehensively evaluated. This narrative review synthesizes the current evidence and discusses the potential physiological mechanisms by which post-exercise thermal interventions may influence nocturnal sleep in athletes. Despite methodological heterogeneity, existing research indicates that post-exercise thermal interventions may influence the subsequent nocturnal sleep of athletes through multiple and varying interacting mechanisms. For example, cold exposure close to bedtime (< 2 h) may disrupt sleep by reducing the distal-to-proximal skin temperature gradient (DPG), thereby increasing sleep onset latency and shortening sleep duration. In contrast, when applied more than 2 h before bedtime, cold exposure may improve sleep by augmenting parasympathetic tone and/or reducing muscle soreness and associated nocturnal movement. Although it remains unclear whether post-exercise heat exposure improves sleep via autonomic modulation or reduced muscle soreness, existing evidence indicates that sleep may be facilitated by an increased DPG. Moderating factors such as sex, time of day, environmental temperature, bedding microclimate, acclimatization status, and training load may influence the effects of post-exercise thermal interventions on sleep and should be investigated in future studies.

1 Introduction

Sleep is considered foundational for optimal performance and recovery in athletes. It has been recommended that athletes obtain 9–10 h of sleep each night [1, 2] and require ~9 h of nighttime sleep to feel rested [3]. However, several studies have shown that athletes frequently obtain insufficient sleep quality and quantity [4, 5], particularly following strenuous physical exertion [6]. Contributing factors may include muscle soreness [7], sympathetic nervous system hyperactivity [8, 9], and sustained increases in core body temperature (CBT) post-exercise [10].

Sleep initiation and maintenance are closely linked with the endogenously-regulated circadian decline in CBT, which typically occurs between 21:00–23:00 and is facilitated by increased heat dissipation from distal skin regions [11]. This thermoregulatory process involves an increase in acral (peripheral) skin temperature accompanied by a decrease in CBT (i.e., the temperature of deep tissues and internal organs, distinct from peripheral skin temperature) and is temporally aligned with the evening rise in melatonin secretion, a hormone that promotes sleep [12, 13]. Modest (between 38.5 °C and 39.5 °C) or severe (> 39.5 °C) elevations in CBT have been consistently observed after exercise in several sports, regardless of the ambient temperature/thermal conditions [14]. Athletes frequently complete their training sessions or participate in competitions late in the evening, a time when CBT would typically begin to decline. It has been suggested that evening exercise-induced increases in CBT may delay this nocturnal decline [15, 16] and therefore disrupt subsequent sleep [17]. Indeed, high strain evening exercise is characterized by sustained increases in CBT and impaired parasympathetic reactivation associated with delayed sleep onset, reduced sleep duration, and poorer sleep quality in a dose-dependent manner [18]. In contrast, lowering CBT before sleep has been proposed to shorten individuals' sleep onset latency, while thermal interventions

Extended author information available on the last page of the article

Published online: 26 October 2026

Key Points

Post-exercise thermal interventions influence sleep, but their effects depend critically on both timing and modality (cooling versus heating)

The distal-to-proximal skin-temperature gradient (DPG) is a key physiological mechanism: manipulating skin temperature (via cooling or heating) alters the DPG, which in turn helps to regulate sleep onset

Individual and contextual factors, such as sex, time of day, environmental temperature, bedding microclimate, acclimatization status, and training load, should be considered when designing post-exercise thermal interventions to optimize sleep in athletes

to reduce CBT during sleep may improve sleep architecture and subjective sleep quality [19, 20].

These thermal interventions include cold exposure (e.g., cold water immersion, whole- or partial-body cryotherapy), heat-exposure (e.g., hot water immersion, sauna, spa, showers), and contrast water immersion [21]. Innovative thermal interventions during sleep (e.g., cooling mattresses) have also been recently explored in athlete populations [22, 23].

Although most studies have reported significant reductions in CBT following post-exercise thermal interventions [24, 25], findings regarding athletes' nighttime sleep are inconsistent. Some studies have shown that alongside CBT reduction, thermal interventions—whether cold or hot—that are applied before or during sleep can improve specific sleep parameters [22, 26, 27]. Conversely, other studies failed to replicate these sleep improvements, suggesting that the decline of CBT alone is likely insufficient to improve sleep [28–30]. These divergent findings suggest that although a reduction in CBT may be necessary for sleep initiation, it is unlikely to be sufficient on its own to meaningfully improve sleep outcomes. The inconsistency in findings across studies may be attributable to several factors, including the potential direct effects of each of the aforementioned thermal interventions on confounding factors that have been shown to influence sleep duration and quality, such as sympathetic hyperactivity, melatonin secretion, muscle soreness, and/or overall perception of recovery [26, 31–33].

Identifying post-exercise thermal interventions that assist in recovery following training and competition while also promoting sleep would significantly benefit elite athletes [2, 34]. However, the influence of post-exercise thermal interventions on both objective (e.g., total sleep time [TST], sleep onset latency [SOL], sleep efficiency [SE], wake after sleep onset [WASO]; sleep architecture: non-rapid eye movement [NREM] sleep, including stages N1, N2, and N3, and rapid-eye movement [REM] sleep) and subjective sleep metrics in athletes has not yet been described in the literature. As such, the physiological mechanisms underpinning the impact of post-exercise thermal interventions on sleep have also not been elucidated. Therefore, the purpose of the current narrative review is to summarize the existing evidence on the effects of post-exercise thermal interventions on subsequent sleep in athletes (as defined in the methods section) and to outline potential underlying physiological mechanisms.

2 Methods

This article is a narrative review informed by a structured literature search designed to identify relevant evidence on post-exercise thermal interventions and sleep in athletes. The review was not conducted as a systematic review, and therefore no formal study quality appraisal or risk-of-bias assessment was performed.

The literature search was conducted using the following major databases: PubMed, Web of Science Core Selection, and Scopus. Databases were searched from inception until 9 June 2025 using the following Boolean expression of keywords: (athlete OR athletes OR well-trained individuals OR recreationally trained individuals) AND (sleep) AND (heat OR warm OR hot OR cold OR shower OR bath OR water immersion OR cryotherapy OR cooling OR hydrotherapy). The literature search was limited to sources published in English. Grey literature was excluded, while conference abstracts were included only when formally published as supplementary material to conference proceedings [35]. In this review, the term cryotherapy refers broadly to cold-air exposure interventions and includes both whole-body cryotherapy (WBC) and partial-body cryotherapy (PBC).

The results were extracted from each database and then imported to EndNote software (version X8.2) for further inspection of duplicates and relevance to the study. To identify supplementary studies, the search was also conducted manually by cross-matching reference lists of included original articles and reviews, performing key author searches, personal communications, and citation tracking of all retrieved papers. The literature search was limited to studies involving athletes, well-trained or recreationally trained individuals, and post-exercise thermal interventions that employed varying ambient or water temperatures or used different bedding microclimates. For the purposes of this review, the term 'athlete' primarily refers to elite and highly trained individuals who engage in structured training in sports with the aim of improving performance or competitive results and who actively participate

in organized sporting competitions [36]. However, the literature in this field includes heterogeneous populations, such as elite, well-trained, and recreationally trained athletes. Furthermore, to elucidate the underlying physiological mechanisms of post-exercise thermal interventions, selected studies involving recreationally active individuals and nonathlete populations were included when they provided relevant mechanistic insights. Figure 1 illustrates the structured literature identification and selection process used for the present narrative review. Thus, the flow chart is included solely to provide a transparent overview of the literature search and study selection process.

3 Results

3.1 Effects of Post-Exercise Cold Interventions on Sleep

Cold water immersion (typically 11 °C to 15 °C for 10–15 min) and whole body cryotherapy (WBC) or partial body cryotherapy (PBC)—typically −180 °C to −60 °C for 3 min—are increasingly used as post-exercise recovery strategies [37–40]. These methods may positively influence factors associated with improved sleep, including reductions in CBT [15], enhanced parasympathetic tone [31, 41], and attenuated muscle soreness [7, 38, 42].

To date, 24 studies have investigated the effects of post-exercise cold interventions on sleep: 13 examining cold water immersion [27, 30, 31, 42–51], and 13 examining WBC or PBC [22, 26, 28, 35, 47, 51–58]. Two studies applied both interventions and are therefore counted in both groups [47, 51].

Seven of the aboventioned studies examined sleep over multiple nights [42, 44, 50, 54–57]. Overall, 12 of the 24 studies (50%) reported improvements in either objective [22, 27, 45, 52, 53, 58, 59] or subjective [31, 35, 43, 47] sleep measures. In contrast, nine studies (37.5%) found no significant effects on objective [22, 28, 30, 48, 57] or subjective [46, 50, 51, 56] sleep measures. One study [44] reported a negative effect on sleep (Table 1).

3.1.1 Cold Water Immersion

One study examined the effects of cold water immersion (30 min post-exercise: 13:00–14:00) in professional cyclists who completed a demanding simulated hill climbing tour, consisting of two 3-day sessions (173.6 ± 14.5 km per day; starting time, 08:00), separated by 2 days of light training. Following each session, athletes underwent cold water immersion (11–12 °C for 10 min) or a sham condition (ultrasound device turned off). Cold water immersion resulted in a 48% reduction in SOL compared with the sham condition [45]. However, other sleep indices such as TST, SE, and subjective sleep quality were negligibly affected. These findings should be interpreted with caution given the relatively small sample size and the possibility that placebo effects may have influenced outcomes despite the sham (inactive-ultrasound) comparison.

Similarly, Chauvineau and colleagues [27] examined the influence of the depth of cold water immersion (13.3 ± 0.2 °C for 10 min) after high-intensity intermittent running exercise in the evening (18:00) on sleep in well-trained endurance runners across three different experimental conditions: (a) whole-body cold water immersion (including head), (b) partial-body cold water immersion up to iliac crest level, and (c) a control condition. Whole-body immersion reduced the time spent in stage 1 sleep by 20% and resulted in fewer nighttime arousals and limb movements (− 74% and −45%, respectively) compared with the control. Additionally, compared with both partial cold water immersion and the control condition, whole-body cold water immersion resulted in a paradoxically greater reduction in parasympathetic activity (root mean square of successive differences [RMSSD]: −65%) and a greater decline in CBT from the 20th to the 40th min of sleep.

In contrast, other studies involving highly-trained individuals [31] and elite team sport athletes [43] and using subjective sleep measures have not corroborated these findings. Specifically, highly trained swimmers who engaged in daily cold water immersion (15 °C for 5 min) following the last training session of each day increased parasympathetic modulation (7–24%) from the 2nd to the 5th day [31]. Additionally, subjective sleep quality was increased (30–38%) from the 2nd to the 4th day compared with a control condition (seated recovery). Similarly, cold water immersion to the sternum (10 °C for 11 min) after fatiguing football (soccer) training during the mid-competitive season reduced mean skin temperature, ameliorated fatigue and stress, and resulted in increased subjective sleep quality in elite players compared with those who underwent passive recovery [43].

However, the positive effects of post-exercise cold water immersion on subsequent sleep were not observed in other studies. In one study [30], 11 male cyclists underwent either no exercise, exercise only (15 min at 75% of peak power and then a 15-min maximal time trial), or exercise followed by cold water immersion (14 °C for 15 min) in the evening (~ 20:00). Cold water immersion decreased CBT during the first 180 min of subsequent sleep by approximately 0.1–0.4 °C compared with exercise only or control conditions. Moreover, mean skin temperature was 0.4–0.7 °C lower at bedtime and for the first 60 min of sleep. Despite the lower proportion of REM sleep (~ 4%) during the initial period of sleep observed following cold water immersion compared with controls, no differences were observed in

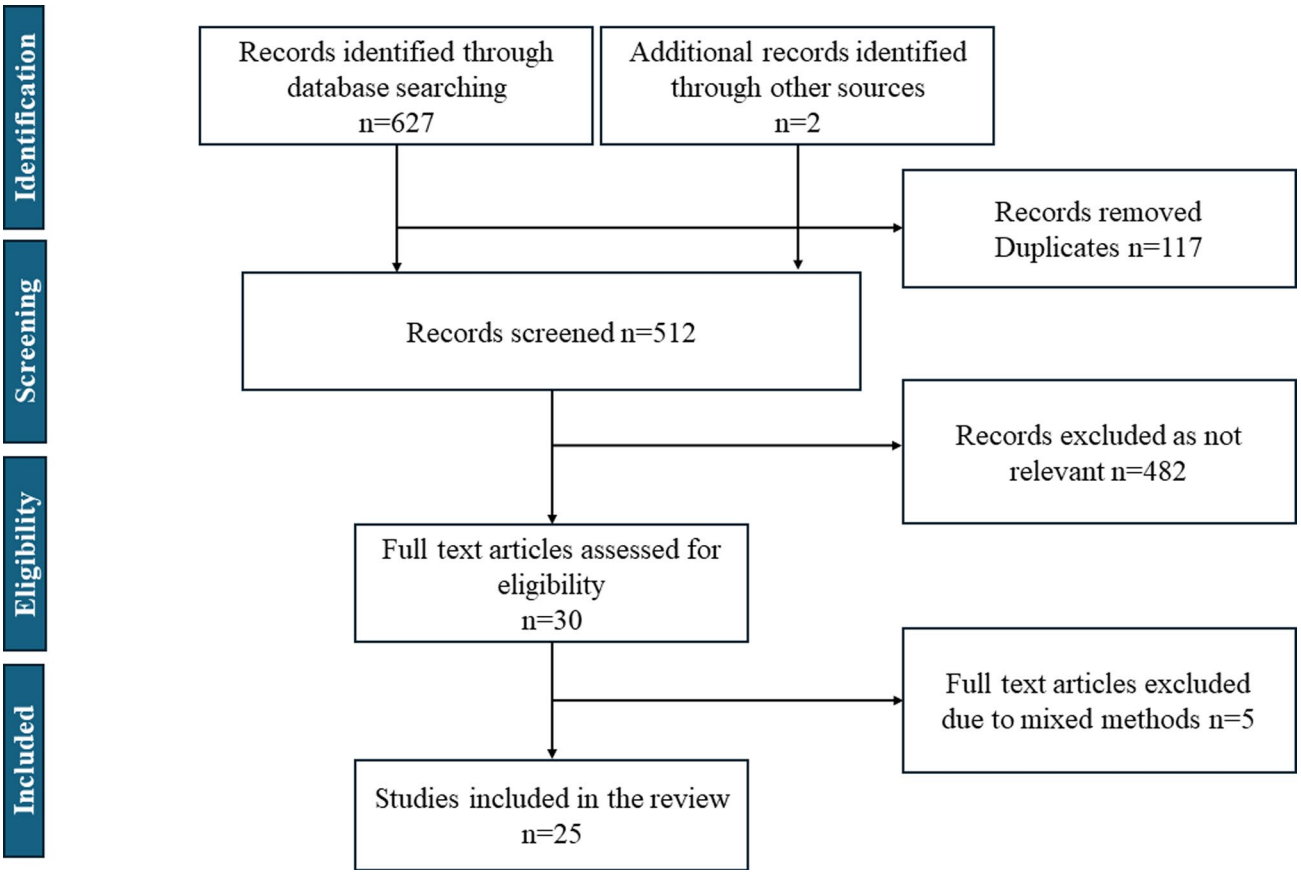


Fig. 1 Flow chart of the narrative review process

TST, SE, WASO, and SOL across conditions either during the initial sleep time or throughout the whole night. Additionally, melatonin and perceived recovery levels remained unchanged.

Previous research findings indicating unchanged nighttime sleep following cold water immersion or cryotherapy are in accordance with observations from earlier [48] and more recent studies [42]. Robey and colleagues [48] evaluated the effect of early-evening (i.e., 16:30–18:30) high-intensity interval training—consisting of vertical jumps and repeated sprints—followed by cold water immersion (14 °C for 15 min) on the sleep of 12 elite youth soccer players. Cold water immersion did not improve TST, SOL, SE, and WASO compared with a passive recovery condition. Similarly, recreationally trained participants who completed five cycling training sessions (mean heart rate, 147–152 beats·min^{-1}; rating of perceived exertion, 14–16 arbitrary units [a.u.]; time that training ended, 17:00) in the heat followed by cold water immersion exhibited similar sleep quantity (TST) and sleep quality (SE, WASO) indices compared with a passive recovery control condition [42].

Consistent with the above findings, three studies have reported no effect of cold water immersion on subjective sleep quality in runners [47], youth field hockey players [50], and volleyball players [46]. Horgan and colleagues [46] reported that cold water immersion after resistance exercise training did not affect the subjective sleep quality of youth volleyball players. Similarly, middle- and long-distance runners who underwent cold water immersion (15 °C for 10 min) immediately after or up to 72 h post-exercise reported no changes in their subjective sleep quality compared with contrast-water immersion or control condition [47].

However, Halson and colleagues [44] reported that, compared with passive recovery, cold water immersion (15 °C for 15 min, four times per week) was possibly associated (according to the authors' predefined probabilistic scale) with impaired SOL and subjective sleep quality of competitive cyclists, following a 39-day period of intensified training and subsequent taper compared with the control.

3.1.2 Cryotherapy

To date, six studies have reported that WBC or PBC following exercise improved sleep quality [26, 35, 47, 53, 58, 59]. Two of these studies [26, 53] reported a reduction

Table 1 Summary of protocols and main findings of studies that have investigated the impact of post-exercise thermal interventions on sleep

Study	Subjects	Exercise Protocol	Post-exercise intervention	Time of intervention	Time Interval between Cold Exposure and Bedtime	Nocturnal Thermal Parameters	Actigraphy	PSG	Subjective Sleep Quality	Other
Ahokas et al., 2023 [65]	$n = 16$ (♂) male basketball players	Complex resistance exercise training (90–95% RM, 60 min)	Infrared sauna (air temperature 43 ± 5 °C; RH = 21%) 20 min versus passive sitting 20 min	Evening (specific time not reported)					↔ sleep	↔ on nocturnal HRV and CK
Al Haddad et al., 2012 [31]	$n = 8$ (♂) highly trained swimmers	Usual training session	5 min either CWI (15 °C) or CON	Morning	> 2 h	–	–	–	CWI:↑ sleep quality	CWI:↑ HRV (Ln RMSSD)
Alexander et al., 2022 [43]	$n = 24$ (♂) elite football players	Fatiguing training session	11 min either CWI (10 °C) or passive rest (CON)	NR		–	–	–	CWI: ↑ sleep quality	CWI: ↓ Tsk
Aloulou et al., 2020 [22]	$n = 19$ (♂) U23 rugby union players performed	Three official games	**1**) MAT (during sleep) **2**) WBC (3 min at −110 °C, 2 h before bedtime) **3**) CON	WBC: at 21:30 MAT: during sleep	WBC: 2 h before bedtime	MAT: ↓ nocturnal CBT compared with CON	MAT: ↓ WASO compared with CON	MAT: ↑ REM compared with CON; MAT: ↔ REM compared with CON	–	WBC: ↑ nocturnal HRV compared with CON; MAT: ↔ nocturnal HRV compared with CON; WBC and MAT: ↔ DOMS, Hooper Index, CK compared with CON
Arc-Chagnaud et al., 2024 [28]	$n = 22$ (♂) well-trained athletes or triathletes	25-min warm-up, HIIT 6 sets at 95% of MAS (3 min) and 3 min of recovery at 60% of MAS	No intervention (CON) − WBC: immediately after training (19:00) or 1 h before going to bed (22:00)	19:00 or 22:00	> 2 h and < 2 h	WBC (22:00): ↓ CBT compared with WBC (19:00) and CON		↔	↔	Both WBC (19:00) and WBC (22:00): ↑ vagal activity (RMSSD, SD1, and LF/HF) but more pronounced in WBC (22:00)

Table 1 (continued)

Study	Subjects	Exercise Protocol	Post-exercise intervention	Time of intervention	Time Interval between Cold Exposure and Bedtime	Nocturnal Thermal Parameters	Actigraphy	PSG	Subjective Sleep Quality	Other
Arc-Chagnaud et al., (2025) [58]	$n = 23$ elite French swimmers (♀ = 7, ♂ = 16)	55 min including 5-min warm up, followed by a continuous exercise bout at: 65% MAS for 25 min and an intermittent exercise bout consisting of 3 sets of 7 min at 85% MAS separated by 2 min of active recovery at 60% MAS	Daily PBC exposure of 3 min at −110 °C was 35 performed (or not) during 5 consecutive days after the evening training	~19:00	> 2 h		↔ sleep duration, sleep onset latency, sleep efficiency, number and duration of awakenings	PBC: ↑ SWS	↔	PBC: ↓ perceived anxiety, tiredness and depression; CRP: ↑ melatonin concentration before the 5th night; ↔ nocturnal HRV α-amylase and cortisol
Bouzigon et al., 2014 [35]	$n = 27$ basketball players participated fully in the study (♀ = 12,♂ = 11)	Training or official game	WBC 3-min exposure between −110 °C and −150 °C in the morning and/or in the evening after a training or match session	Morning and/or evening	> 2 h				↑ Spiegel's questionnaire	
Chauvineau et al., 2021 [27]	$n = 12$ (♂) well-trained endurance runners	Simulated trial	10 min of: 1) whole body (head included) CWI, 2) partial body (iliac crest) CWI, and 3) CON	19:55	> 2 h	Both WBC and PBC: ↓ CBT compared with CON	Both WBC and PBC: ↓ arousal compared with CON WBC: ↓ limb movement compared with CON: WBC: ↑ SWS compared with CON		Both WBC and PBC: ↑ sleep quality compared with CON	WBC: ↓ RMSSD, ↓ LF, ↓ HF; compared with PBC and CON versus partial whole versus partial and CON: ↔ muscle damage, CK, and subjective ratings

Table 1 (continued)

Study	Subjects	Exercise Protocol	Post-exercise intervention	Time of intervention	Time Interval between Cold Exposure and Bedtime	Nocturnal Thermal Parameters	Actigraphy	PSG	Subjective Sleep Quality	Other
Chauvineau et al., 2023 [23]	$n = 21$ (♂) endurance runners	2 week usual training—2 week overload—2 week tapering	HMT versus LMT	During sleep			↔		↔	
Chauvineau et al., 2024 [29]	$n = 21$ (♂) well-trained endurance runners	2 week usual training—2 week overload (+40%) training duration)—2 week tapering (−50% training duration)	HMT $n = 11$ versus LMT $n = 10$; at the end of baseline (test 1), overload (test 2), and taper (test 3) athletes visited the lab to record sleep with PSG	During sleep		Test 2 versus test 1: ↑ CBT for LMT; test 2 versus test 1: ↓ CBT for HMT		↔		
Douzi et al., 2019 [52]	$n = 22$ (♂) physically active	55 min duration: 25 min continuous at 65% of MAS and 25 min intermittent running (85% of MAS alternated with 60% of MAS	3 min passive recovery (CON) or WBC (3 min at −40 °C)	~20:30	> 2 h		WBC: ↑ sleep efficiency +5%		WBC: ↑ sleep quality	WBC: ↑ HF, ↓ LF, and ↓ LF/HF during SWS
Douzi et al., 2019 [26]	$n = 9$ (♂) professional soccer players	10-min warm-up—30-min technical—30-min tactical—20-min conditioning (15 × 15 s at 95% MAS with passive rest)—20-min plyo	1) PBC (excluding head/neck) (−180 °C; 180 s); 2) PBC 2 × 90 s with 5 min rest in neutral environment; 3) PBC (90 s); and 4) CON (no exposure)	13:00 to14:00	> 2 h	180 s: ↓ Tsk in 2 × 90 s compared with 90 s; ↔ Tsk in 2 × 90 s compared with 90 s	180 s: ↓ number of movements compared with the control		↔	↔ HRV

Table 1 (continued)

Study	Subjects	Exercise Protocol	Post-exercise intervention	Time of intervention	Time Interval between Cold Exposure and Bedtime	Nocturnal Thermal Parameters	Actigraphy	PSG	Subjective Sleep Quality	Other
Grainger et al., 2020 [56]	$n = 18$ (♂) professional rugby athletes	Competitive phase of a playing season (12 weeks)	PBC 2 min at −120 °C/ washout periods (4 weeks)/ control condition	Between 10:00 and 12:00	> 2 h				↔ sleep quality	↔ on wellness and muscle soreness
Halson et al., 2014 [44]	$n = 34$ (♂) competitive cyclists	7 days of baseline training (low volume), 21 days of intensified training [(increasingly weekly load-three interval sets were also completed each week, HIIT, 2 MMP 4 min, and a third high-intensity interval training set (set 3)], and an 11-day taper (overall training duration was reduced extensively to allow for a taper period)	Cyclists were randomized to CWI for four times per week for 15 min at 15 °C or control (passive recovery) groups	NR			CWI: ↓ sleep latency			CWI: ↓ REST-Q measures
Haq et al., 2022 [51]	$n = 33$ (♂) non-athletes	Downhill (15%) running at 60% VO_{2max}—WBC versus CWI versus CON	WBC1 (1 h after exercise) versus WBC4 (4 h after exercise) versus CWI (1 h after exercise)	NR		NO	↔ sleep efficiency and total time via sleep tracking wrist watches		↔	↔ inflammation, femoral blood flow

Table 1 (continued)

Study	Subjects	Exercise Protocol	Post-exercise intervention	Time of intervention	Time Interval between Cold Exposure and Bedtime	Nocturnal Thermal Parameters	Actigraphy	PSG	Subjective Sleep Quality	Other
Horgan et al., 2023 [46]	$n = 18$ junior elite and well-trained volleyball players	Resistance training 5 × 10 at 75 RM; training duration: 75 min	CON: at ~24 °C; CWI: at ~15 °C; CWT: at 7 × 2 min, alternating hot (~ 39 °C) and cold (~ 15 °C); or HWI: ~39 °C, 30 min post-exercise	Evening—not specified	> 2 h				HWI: ↑ perception of sleep compared with CWT	HWI: ↑ perception of fatigue and testosterone levels compared with CWT; ↔ on hormones (testosterone/cortisol, [T:C] ratio) or perception
Kim et al., 2025 [57]	$n = 14$ (♂) Division 1 collegiate basketball athletes	Battery of performance tests (a maximum repetition bench press test, a maximum repetition pull-up test, a vertical jump test, a 10-yard sprint, a 3/4 court [22.86 m] sprint, and a lane agility test)	PBC 2 min at −120 °C versus control	18:00 to 19:00	> 2 h		PBC: ↔ sleep		PBC: ↔ Pittsburgh Sleep Quality Index (PSQI-K)	
Krueger et al., 2020 [50]	$n = 18$ (♂) field-hockey players (U18 national squad)	Training or official game (tournament)	$n = 9$ daily CWI (5 min at 6.4 ± 0.8 °C, excluding the head) versus passive recovery (CON, $n = 9$)	Afternoon—not specified	> 2 h	CWI: ↓ Tsk during			CWI: ↔ sleep quality	CWI: ↔ DOMS, LDH, blood urea nitrogen, and CK

Table 1 (continued)

Study	Subjects	Exercise Protocol	Post-exercise intervention	Time of intervention	Time Interval between Cold Exposure and Bedtime	Nocturnal Thermal Parameters	Actigraphy	PSG	Subjective Sleep Quality	Other
Lastella et al., 2019 [45]	$n = 10$ (♂) professional cyclists	Simulated hill climbing tour consisting of two 3-day sessions (140–190 km per day) separated by 2 days where ~60 km recovery rides were performed	CWI at 11–12 C for 10 min) OR placebo (ultrasound turned off; 10 min)	13:00 to 14:00	> 2 h		CWI: ↓ sleep latency	-		
Malone et al., 2022 [54]	$n = 16$ (♂) premier league players	2 years in season games	WBC: low (− 114 ± 2 °C for 133 ± 2 s), medium (− 121 ± 1 °C for 173 ± 2 s) and high (− 133 ± 1 °C for 181 ± 2 s) cryotherapy exposure indexes (CEI)	No standardized window of exposure		–	–	–	↔ wellness questionnaire across conditions	Low and high CEI: ↓ salivary markers with chronic exposure
Mihailovic et al., 2024 [53]	$n = 16$ (♂) trained cyclists	RSH consisted of 3 sets of 5 × 10 s sprints with 20 s recovery at a simulated altitude of 3000 m	RSH, WBC + RSH, RSH + WBC	NR		–	RSH + WBC: ↓ *n* of movement compared with RSH and WBC + RSH	–	↔ Spiegel sleep quality across conditions	WBC + RSH and RSH + WBC: ↔ HRV WBC + RSH and RSH + WBC: ↑ recovery perception versus RSH
Qu et al., 2022 [47]	$n = 12$ (♂) secondary national-level middle- and long-distance runners	90-min treadmill running and a jump step exercise	CWI, CWT, CRYO, or control (CON)	NR					CRYO versus CWI and CWT: ↑ Pittsburgh Sleep Quality	CRYO versus CWI: ↓ IL-6; CRYO and CWT versus CWI and CON: ↓ LDH

Table 1 (continued)

Study	Subjects	Exercise Protocol	Post-exercise intervention	Time of intervention	Time Interval between Cold Exposure and Bedtime	Nocturnal Thermal Parameters	Actigraphy	PSG	Subjective Sleep Quality	Other
Robey et al., 2013 [30]	$n = 11$ (♂) cyclists	15 min at 75% VO_{2max} and 15 min at maximal time trial versus NO EXE	CWI versus CON immediately after training	20:00	> 2 h	CWI: ↓ CBT and Tsk			↔ sleep	↔ melatonin
Robey et al., 2014 [48]	$n = 12$ (♂) elite youth soccer players	Vertical jumps and repeated sprints	CWI versus CON immediately after training	19:00	> 2 h		↔ bedtime, wake time, sleep duration, sleep onset latency, sleep efficiency and wake after sleep onset		↔ self-rated scores of sleepiness at bedtime and wake, plus overall sleep quality	
Schaal et al., 2015 [55]	$n = 10$ (♀) elite synchronized swimmers	1 week normal training (BASE)—1 week intensified training with no intervention (control)—1 week intensified training using WBC	WBC versus CON after training	18:00 to 19:00	> 2 h	–	–	WBC: ↑ sleep quantity		↔ La, HR, salivary cortisol
Skein et al., 2018 [42]	$n = 30$ (♂) recreationally trained	(i) 90 min cycling at 40% P_{max}; (ii) 90 min cycling at 40% P_{max}; or (iii) 30 min cycling alternating between 40 and 70% P_{max}	1) 15 min passive recovery after 90 min exercise, $n = 10$; 2) 15 min CWI after 90 min exercise, $n = 10$; 3) 15 min passive recovery after 30 min exercise, $n = 10$	17:00	> 2 h		↔ on 1) sleep latency, 2) efficiency, 3) total time in bed, 4) total time asleep wake after sleep onset, 5) number of awakenings, and 6) awake duration during baseline and heat training		↔ subjective sleep	↔ POMS

Table 1 (continued)

Study	Subjects	Exercise Protocol	Post-exercise intervention	Time of intervention	Time Interval between Cold Exposure and Bedtime	Nocturnal Thermal Parameters	Actigraphy	PSG	Subjective Sleep Quality	Other
Tabben et al., 2018 [49]	$n = 12$ (♂) MMA athletes	MMA combat	CWI versus CON	08:00 to 10:00	> 2 h				CWI: ↑ sleep	CWI: ↑ Hooper Index, ↓ DOMS, fatigue sensation, perceived stress
Whitwort-Turner et al., 2017 [64]	$n = 11$ (♂) youth soccer players	3 consecutive days/measurements for each condition: MD − 1, MD, and MD + 1	10 min shower (40 °C) 20 min before bedtime versus control (post-session showering only, > 8 h before bedtime)	20 min before bedtime		Shower: ↑ DPG and ↑ distal Tsk signal effect within the first 30 min after lights out	Shower: ↓ sleep latency (− 7 min), ↑ sleep efficiency (+ 2%),	–	↔ sleep	–

Objective sleep assessments refer to polysomnography and/or actigraphy measurements, while subjective sleep assessments refer to the use of questionnaires and/or sleep diaries

↑ indicates improvement; ↓ indicates deterioration; ↔ indicates unchanged, *CWI* cold water immersion, *CWT* contrast water therapy, *MAT* mattress, *LMT* low-heat-capacity mattress, *HMT* high-heat-capacity mattress, *WBC* whole body cryotherapy, *PBC* partial body cryotherapy, *CON* control group/conditio, *HWI* hot water immersion, *Tsk* skin temperature; *DPG* distal-to-proximal temperature gradient, *CBT* core body temperature, *WASO* wake after sleep onset, *REM* rapid eye movement, *SWS* slow-wave sleep, *DOMS* delayed onset muscle soreness, *CRP* C-reactive protein, *CK* creatine kinase, *LDH* lactate dehydrogenase, *CEI* cryotherapy exposure indexes, *HRV* heart rate variability, *LF* low frequency, index of HRV, *HF* high frequency, index of HRV, *RMSSD* root mean square of successive respiratory-to-respiratory (R–R) interval differences, index of HRV; *SD1* standard deviation 1, in Poincaré plot, the standard deviation perpendicular to the line-of-identity, *MAS* maximal aerobic speed, *HR* heart rate, *RSH* repeated sprint in hypoxia, *REST-Q* Recovery and Stress Questionnaire

in nocturnal body movements, an indicator of improved sleep quality [60]. For example, Douzi and colleagues [26] exposed nine professional soccer players to PBC (− 180 °C for 3 min) or passive recovery following a midday training session (time of training, 12;00) involving high-intensity interval running and plyometric exercises. Cryotherapy reduced nocturnal movement by two-thirds compared with the control [26]. Similarly, trained cyclists who performed repeated-sprint training in hypoxia experienced less movement during sleep after WBC (− 60 °C for 3 min) compared with passive recovery [53].

Athletes' sleep may be disturbed during or after intensified training periods [61, 62], potentially contributing to overreaching or overtraining [61]. Schaal and colleagues [59] tested whether daily WBC (− 110 °C for 3 min) would preserve sleep quantity and quality in elite synchronized swimmers undergoing intensified training (+ 125% load compared to baseline). In the cryotherapy condition, TST and SE were maintained. In contrast, these parameters significantly deteriorated when cryotherapy was not implemented. Similarly, a recent study [58] found that elite swimmers exposed to PBC (− 110 °C for 3 min) following five consecutive evening high-intensity training sessions (time of PBC intervention, 19:00) experienced longer duration of slow-wave sleep (SWS) during the first part of the night compared with a passive recovery condition. However, other important measures such as SOL, TST, SE, and the number and duration of awakenings remained unchanged. Notably, the increase in SWS was more pronounced in poor sleepers.

The beneficial sleep effects of cryotherapy have not been consistently replicated in other studies [22, 28, 56, 57]. For example, Aloulou and colleagues [22] investigated the influence of WBC (− 110 °C for 3 min) administered 4 h after a rugby union match and 2 h before bedtime (~ 21:30) on the sleep of 23 elite youth athletes. WBC had only a trivial effect on sleep architecture (light sleep, SWS, and NREM and REM sleep proportions) and did not affect nocturnal CBT or nocturnal heart rate variability. Similarly, a more recent study [28], using wireless electroencephalogram (EEG) headbands, examined whether the timing of WBC (− 110 °C for 3 min at 19:00 versus 22:00) influenced subsequent sleep in well-trained male athletes, following high-intensity exercise (six 3-min sessions at 95% of maximal aerobic speed with 3 min of active recovery). Although WBC at 22:00 increased nocturnal heart rate variability (+ 30%) and lowered nocturnal CBT, it did not affect sleep (TST, NREM sleep duration, REM sleep duration, SWS duration, SE, WASO, movements count, and perceived sleep quality) compared with a control [28]. A recent study also found that daily WBC had no effects on subjective sleep in elite soccer players [54].

3.1.3 Effects of Post-Exercise Cold Interventions on Sleep: Summary of the Findings

Collectively, evidence regarding the effects of post-exercise cold water immersion and cryotherapy on athletes' nocturnal sleep is mixed. While approximately half of the 24 studies reviewed reported improvements in either objective or subjective sleep outcomes, the specific benefits were inconsistent across protocols, modalities, and populations. For example, other studies found no significant impact on sleep quantity, efficiency, or quality and one study reported potential negative effects. Overall, the current literature suggests that although post-exercise cold interventions may improve sleep under specific conditions (e.g., timing, training load, individual responsiveness), their efficacy and effectiveness are not yet conclusive and warrant further investigation, perhaps using standardized protocols or dose–response designs.

3.2 Effects of Post-Exercise Heat Interventions on Sleep

Passive body heating before bedtime has been proposed as a strategy to improve sleep [63]. However, relatively few studies have investigated the effects on sleep in athletes [22, 23, 29, 46, 64, 65]. Specifically, three studies have examined the impact of post-exercise warm showers [64], hot water immersion [46], and infrared sauna [65] on sleep.

3.2.1 Hot-Water Exposure

Whitworth–Turner and colleagues [64] measured the effects of a 10-min hot shower (40 °C), taken 20 min before bedtime on objective sleep and skin temperature in 11 male soccer players following either a training or a match. Compared with a control condition, the hot shower increased distal skin temperature by 1.1 °C both 5 min before and 30 min after bedtime, as well as the distal-to-proximal skin temperature gradient (DPG) by 0.7 °C at 30 min post-bedtime. These thermoregulatory changes were accompanied by significant improvements in SOL (− 7 min) and SE (+ 2%). Similarly, another study reported that hot-water immersion (39.1 ± 0.5 °C) after 30 min of resistance training led to moderate to large improvements in subjective sleep quality in volleyball players compared with the control condition (rested seat), cold water immersion (14.8 ± 0.2 °C), and contrast-water immersion, in whom subjective sleep quality remained unchanged [46].

3.2.2 Sauna

To date the only study that has investigated the use of infrared sauna (air temperature, 43 °C) following resistance

training showed no effect on subjective sleep measures compared with passive sitting [65].

3.2.3 Effects of Post-Exercise Heat Interventions on Sleep: Summary of the Findings

Overall, current evidence on post-exercise heat exposure and sleep in athletes is limited and mixed. Acute post-exercise heat exposure through hot showers and hot water immersion was associated with improved sleep onset latency, efficiency, and subjective sleep quality in one study only. In contrast, one study only using infrared sauna exposure did not demonstrate benefits on subjective sleep quality. It should be noted that the available studies examined both water-based (hot shower and hot-water immersion) and air-based (infrared sauna) heating modalities, which differ in the way they transfer heat. Water-based methods warm the body primarily through direct conduction and convection, producing a rapid rise in skin temperature, whereas air-based heating warms the body more gradually. These differences may influence the magnitude and time course of DPG and could partly account for the divergent sleep outcomes observed across the few available studies. Although acute heat exposure before bedtime appears promising, more research is needed to confirm its efficacy and effectiveness.

3.3 High-Heat-Capacity Mattresses: Nocturnal Thermoregulation and Sleep

Krauchi and colleagues [20] demonstrated that sleeping on a high-heat-capacity mattress enhances SWS in untrained individuals. This innovative approach facilitates a continuous removal of body heat during sleep (i.e., cooling). High-heat-capacity mattresses absorb and conduct large amounts of heat, thereby promoting heat dissipation. Krauchi and colleagues [66] reported that sleeping on a high-heat-capacity mattress reduced CBT significantly after 70 min and reached a maximum difference (− 0.3 °C) 5 h after lights off compared with sleeping on a low-heat-capacity mattress. Three further studies by this group [22, 23, 29] have examined whether similar effects occur in athletes following exercise. Aloulou and colleagues [22] investigated the acute (single night) use of a high-heat-capacity mattress after rugby union matches on sleep architecture in 19 elite youth male athletes. The results demonstrated reduced WASO (− 10.5 min), higher REM sleep proportion (+ 2.8%), a trend toward higher SE (+ 2.9%), and lower mean CBT (− 0.1 °C) with a high-heat-capacity mattress compared with the control condition. Indices of autonomic nervous system balance (including heart rate and heart rate variability) and subjective fatigue remained unchanged between conditions. However, the positive effects of chronic use of a high-heat-capacity mattress on nocturnal sleep were not confirmed by other investigations [23, 29]. For example, the use of a high-heat-capacity mattress (1.18 m^2 K W^{-1}; 28 °C) had no significant effect on sleep-related indices measured by polysomnography, compared with a low-heat-capacity mattress (1.63 m^2 K W^{-1}; 28 °C) in trained endurance runners following 2 weeks of overload and a taper [29]. CBT was moderately higher (+ 0.1 °C) in the low-heat-capacity mattress group at the post-overload period compared with pre-overload, and a trivial reduction was recorded for the high-heat-capacity mattress group (− 0.03). However, it is important to note that this study lacked a control group. Further, an earlier study from the same research group using a similar experimental protocol reported that sleep parameters measured by actigraphy were unchanged with the use of a high-heat-capacity mattress [23]. Recent studies using a temperature-controlled mattress cover have shown promising improvements in both objective and subjective sleep indices in healthy adults [67, 68]; however, the effectiveness of this intervention has not yet been evaluated in an athletic population.

3.3.1 High-Heat-Capacity Mattresses: Summary of the Findings

One study that examined the acute use of high-heat-capacity mattresses post-exercise to remove body heat showed a reduced wake-after-sleep onset and increased REM sleep. However, studies examining the chronic use of high-heat-capacity mattresses after exercise have reported no significant benefits on objective sleep outcomes. Evidence supporting its long-term effectiveness remains inconsistent.

4 Discussion

The findings of studies investigating the effects of post-exercise thermal therapies on sleep-related parameters in athletes are equivocal. While some have shown improved nocturnal sleep, others have found unchanged or even disturbed sleep using both objective and subjective sleep measures. The physiological mechanisms that may explain the discrepancies among these studies are likely related to the effect of the interventions (e.g., cold or hot) on thermoregulatory and autonomic function, as well as on muscle soreness or fatigue markers, all of which have been shown to affect athletes' sleep. The mechanistic pathways hypothesized to underlie the influence of post-exercise thermal interventions on sleep are illustrated in Fig. 2 (cold exposure) and Fig. 3 (heat exposure).

4.1 Thermoregulation and Circadian Function

4.1.1 Core Body Temperature and Sleep Regulation

CBT, governed by the balance between heat production and heat loss, serves as a key circadian marker tightly linked to sleep regulation [69, 70]. Prior to habitual bedtime (21:00–23:00), a circadian-driven decline in CBT promotes sleep initiation and facilitates subsequent sleep continuity and efficiency [15]. This decline primarily results from increased heat dissipation from the proximal to distal regions [71, 72].

Athletes who normally compete or train in the evening (e.g., 18:00–21:00) may experience significant increases in CBT (> 38.5 °C), which may remain elevated for a prolonged period after the cessation of exercise [30], regardless of ambient thermal conditions [14]—particularly when exercise is strenuous. Elevated CBT post-exercise has been proposed as a contributing factor to nighttime sleep disturbances [17, 33], while a reduction in CBT may serve as a potential facilitator of sleep [58].

4.1.2 Impact of Exercise Timing on Thermoregulation and Sleep

The proposed impact of post-exercise thermal interventions, either cold (water temperature < 15 °C, air temperature not less than − 180 °C) or heat (water temperature: about 40 °C), on nighttime sleep are presented in Fig. 2 and Fig. 3, respectively. Here, we present five studies [22, 27–30] that concurrently assessed CBT and both objective and subjective sleep parameters during sleep following post-exercise cold or heat exposure. Of these studies, four [22, 27–29] demonstrated that CBT drops significantly after both cold and heat interventions. However, some studies employed protocols in which training concluded before 21:00 [22, 27, 45]; whereas

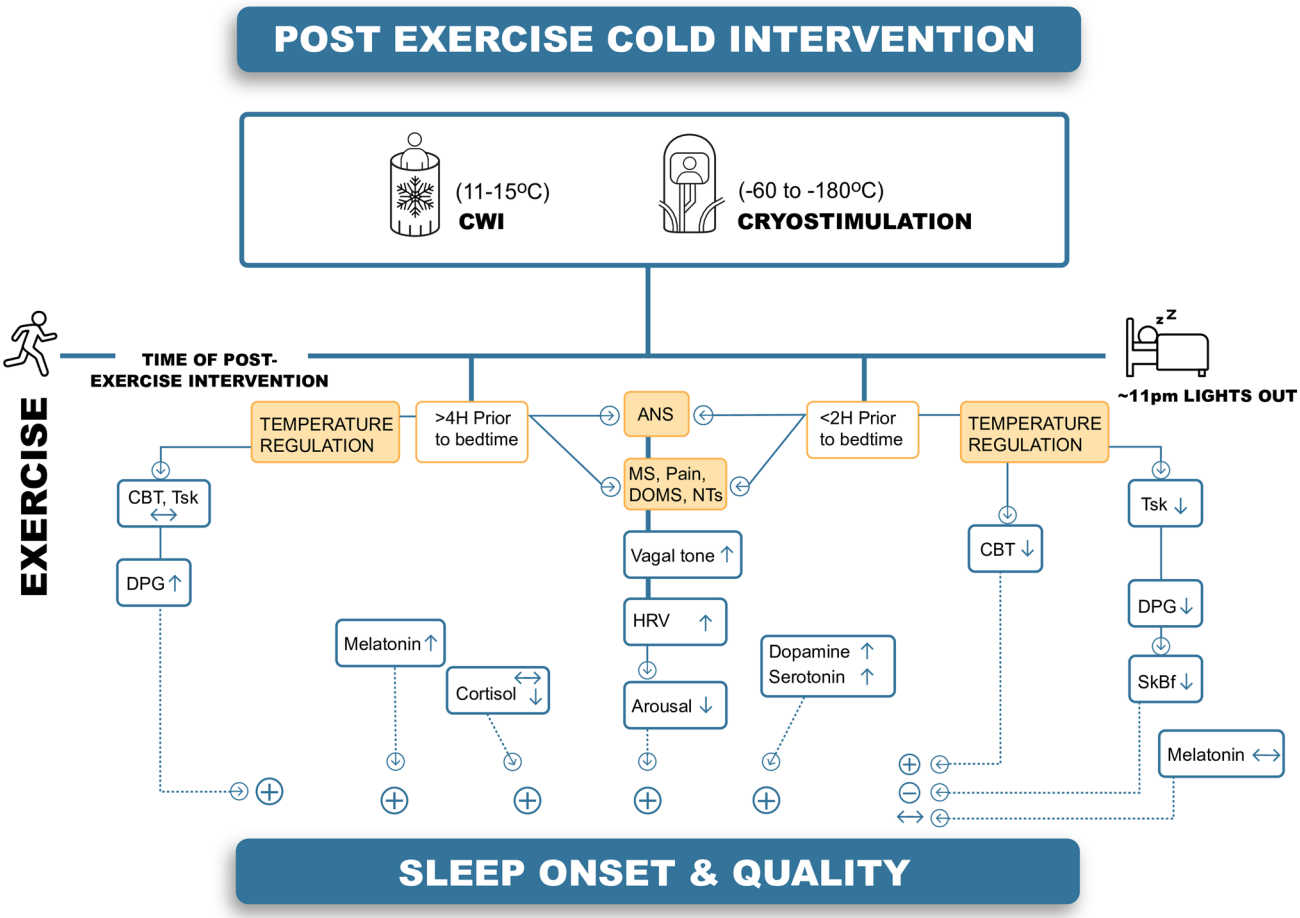


Fig. 2 Physiological mechanisms underpinning the impact of post-exercise cold interventions on sleep. Dotted line indicates the final outcome; solid line indicates the cascade of effects; + indicates positive outcome effect; − indicates negative outcome effect; ↔ indicates inconclusive or no effect. *CWI* cold water immersion, *cryostimulation* frozen dry air exposure, *CBT* core body temperature, *Tsk* skin temperature, *DPG* distal-to-proximal skin temperature gradient, *SkBf* skin blood flow, *MS* muscle soreness, *NTs* neurotransmitters, *DOMS* delayed onset muscle soreness, *ANS* autonomic nervous system, *HRV* heart rate variability

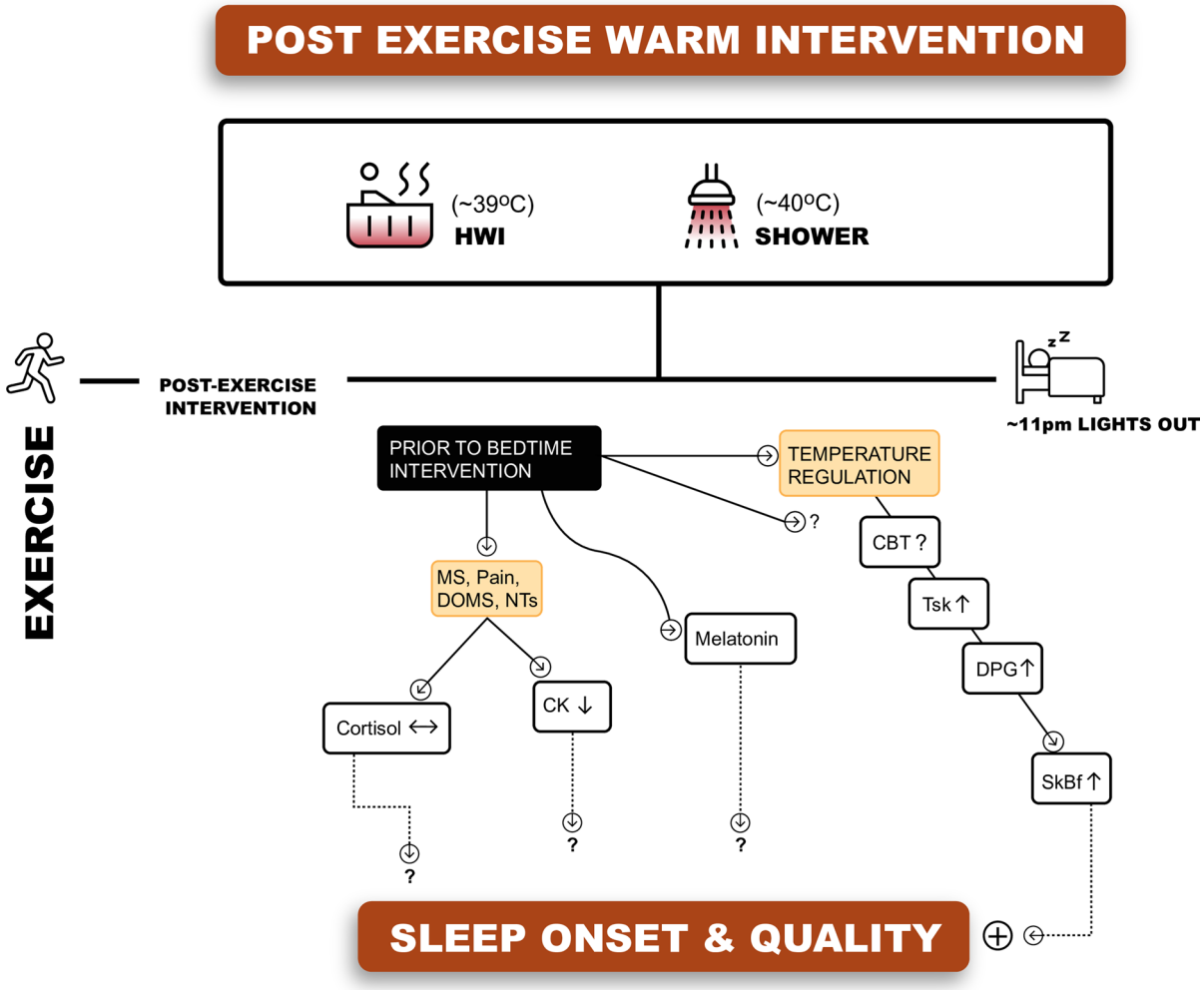


Fig. 3 Physiological mechanisms underpinning the impact of post-exercise warm interventions on sleep. Dotted line indicates the final outcome; solid line indicates the cascade of effects; ? indicates no data; +indicates positive outcome effect; − indicates negative outcome effect; ↔ indicates inconclusive or no effect. *HWI* hot water immersion, *CBT* core body temperature, *Tsk* skin temperature, *DPG* distal-to-proximal skin temperature gradient, *SkBf* skin blood flow, *MS* muscle soreness, *NTs* neurotransmitters, *DOMS* delayed onset muscle soreness, *ANS* autonomic nervous system, *HRV* heart rate variability

in other studies the training end time was not reported [28, 29]. The time of exercise completion is an important consideration because the exercise-related increase in CBT may interfere with the natural circadian drop in CBT that normally occurs late in the evening (21:00–23:00) and may affect the initiation, continuity, and quality of sleep [18]. Of note, two studies using cold water immersion reported positive effects of post-exercise cold exposure on athletes' nocturnal sleep using training protocols and interventions that were conducted either in the afternoon (13:00–14:00) [45] or early evening (18:00) [27]. In any event, the findings of the present review suggest that improvements in nighttime sleep are unlikely to be attributed by the lowering of CBT alone.

4.1.3 Distal to Proximal Skin Temperature Gradient and Sleep

To date, several studies have experimentally demonstrated that sleep onset is facilitated when an increase in peripheral (i.e., skin) temperature and corresponding elevations in skin blood flow modulation occur beforehand [12, 73, 74]. Krauchi and colleagues (2000), in young non-athletes, observed that in free-living conditions the distal-to-proximal skin temperature gradient is a significant predictor of sleep onset latency, whereas CBT and CBT rate of change are not [66]. This finding may explain why heat-based interventions after training may improve sleep (Fig. 3). Whitworth–Turner and colleagues (2017) showed that a hot shower after training and before bedtime improved sleep in 11 soccer players,

inducing a significant decrease in sleep onset latency and an improvement in sleep efficiency (+2.0%) [64]. These outcomes were attributed to: (i) an increased distal skin temperature observed just before and following bedtime, and (ii) an increased distal-to-proximal skin temperature gradient 30 min following bedtime. Similar improvements in athletes' sleep have been reported by some [22] but not all studies using high-heat-capacity mattresses during sleep following evening exercise in athletes [23, 29]. Aloulou and colleagues (2020) found that rugby players who slept on a high-heat-capacity mattress after a game (ending at 15:00, bedtime at 23:30) demonstrated lower wake-after-sleep onset and higher proportions of REM sleep when compared with sleeping on a typical mattress [22]. The discrepancy of these results may be attributed to different methodological assessments of sleep (polysomnography versus actigraphy; Table 1), the number of days during which data were recorded, or the unique specifications of the heat-capacity mattresses. Recent work in non-athletes is consistent with the aforementioned evidence by demonstrating that sleeping on a high-heat-capacity mattress increased nocturnal stage N3 sleep compared with sleeping on a low-heat-capacity mattress [74]. Moreover, it was found that participants with a greater degree of body cooling (e.g., increased CBT proximal back skin temperature gradient) exhibited a more pronounced increase in N3 sleep and a decrease in REM sleep. Despite methodological differences, these studies suggest that the distal-to-proximal skin temperature gradient, rather than CBT decline alone, plays an important role in sleep promotion. Body cooling achieved through exposure to thermal interventions, either by heating prior to sleep or by enhancing conductive heat loss using a high-heat-capacity mattress during sleep, can effectively increase the distal-to-proximal skin temperature gradient. As such, this approach may be more beneficial than post-exercise cold exposure, which may exacerbate peripheral vasoconstriction and consequently blunt or delay heat transfer to the skin [75]. The proposed impact of cooling interventions using either high-heat-capacity or low-heat-capacity mattresses during sleep is presented in Fig. 4.

4.1.4 Melatonin Secretion

Secretion of the hormone melatonin is an important component of the normal circadian rhythm of CBT and plays a key role in the regulation of sleep. Changes in melatonin secretion serve as a phase marker of the internal circadian clock [12, 13], as its gradual increase and peak in the late evening coincides with the decline of CBT and initiates the body's preparation for sleep. However, to date, the few studies which have evaluated the influence of different post-exercise thermal interventions on melatonin concentration have reported conflicting results [30, 76]. For example, a study showed that after the completion of either post-exercise cold (14 °C) or neutral water (34 °C) immersion (18:00–20:00), CBT significantly reduced over time but the typical increase in melatonin secretion remained unaffected by water temperature 90 min post-immersion [76]. Consistent with this finding, most sleep-related parameters measured with actigraphy and polysomnography remained unchanged, even though the timing of cold water immersion aligned with the circadian drop in CBT. This observation was evident despite the significant reduction of CBT compared with the control condition [30]. In contrast, Arc-Chagnaud and colleagues (2025) recently demonstrated an increase in melatonin concentration after repeated whole-body cryotherapy (WBC) accompanied by a significant reduction in CBT and improvements in objective measures of sleep [58]. The discrepancy between the two cold interventions could rely on the method of body cooling (cryotherapy versus cold water immersion) and their potential effects on melatonin. To the best of our knowledge there is no study comparing these two cold interventions on melatonin response.

Collectively, the timing of exercise and the type of post-exercise thermal interventions, applied before sleep (e.g., cold water immersion, cryotherapy, hot water immersion/shower) or using heat dissipation interventions during sleep (e.g., high-heat-capacity mattress), may explain some of the differences reported across studies. Herein, we postulate that post-exercise cold exposure likely does not promote sleep via thermoregulatory mechanisms, whereas post-exercise heat dissipation interventions may enhance sleep by inducing distal vasodilation, thereby increasing the distal-to-proximal skin temperature gradient [66]. It is currently unclear whether post-exercise cold exposure or warm applications affect the release of melatonin.

4.1.5 Timing of Cold Exposure: A Critical Consideration

Evidence suggests that cold water immersion lowers skin temperature for several hours after cessation of exposure [30]. This decrease in skin temperature may induce distal vasoconstriction, which plays a key role in sleep initiation, potentially leading to delayed sleep onset [72]. In contrast, cold exposure applied more than 4 h before bedtime may reduce inflammation and muscle soreness without disrupting circadian thermoregulation, thus supporting sleep [27, 49, 58]. The timing of post-exercise cold application may be a critical factor, as applying it too close to bedtime, particularly within 2 h, may interfere with circadian thermoregulatory processes (Table 1). However, this timing effect has not been systematically tested, and the proposed < 2 h threshold should be interpreted as a conceptual hypothesis derived from recurring patterns across studies, rather than a formally validated threshold. Across the reviewed studies, cold exposure applied in the afternoon and early evening (i.e., several

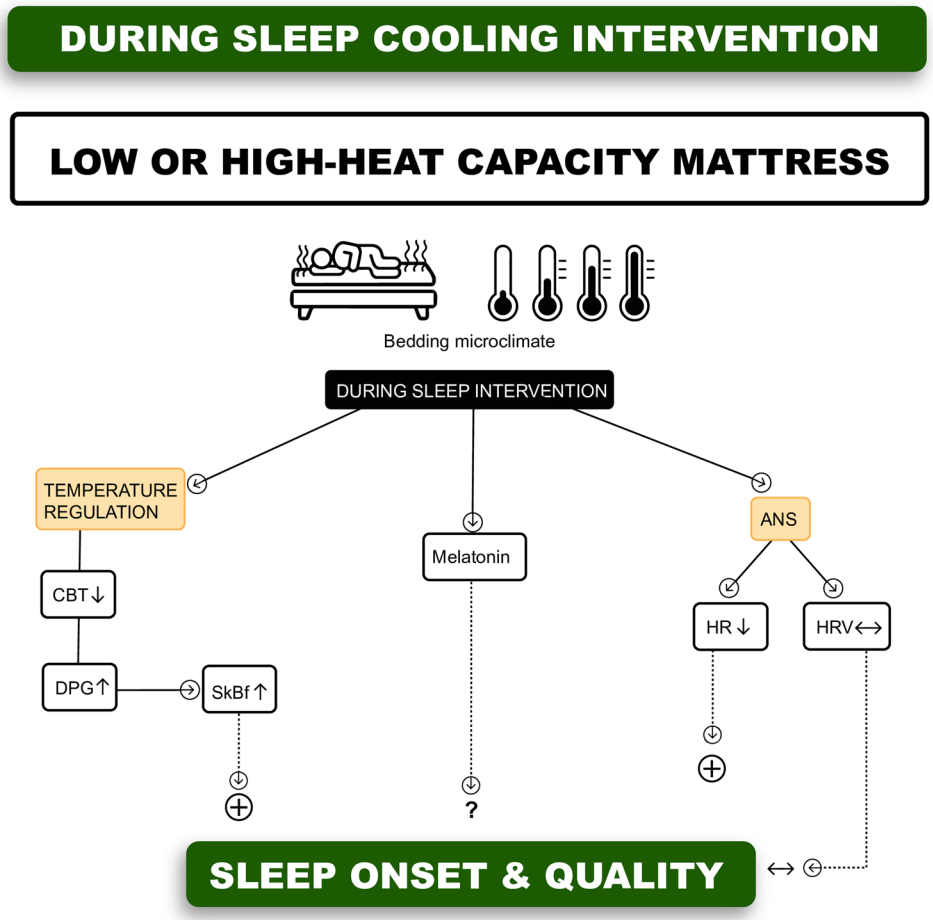


Fig. 4 Physiological mechanisms underpinning the impact of cooling interventions during sleep. Dotted line indicates the final outcome; solid line indicates the cascade of effects; ? indicates no data; + indicates positive outcome effect; ↔ indicates inconclusive or no effect. *CBT* core body temperature, *DPG* distal-to-proximal skin temperature gradient, *SkBf* skin blood flow, *ANS* autonomic nervous system, *HR* heart rate, *HRV* heart rate variability

hours prior to bedtime) was generally associated with favorable sleep outcomes, whereas reports of impaired or absent benefit tended to involve cold exposure closer to bedtime (Table 1). Importantly, only one study has experimentally manipulated the timing of cold exposure within a single protocol, and it reported no difference in sleep outcomes between early- and late-evening application [28]. Therefore, the proposed < 2 h threshold reflects a pattern observed between studies rather than an effect demonstrated within studies through direct experimental manipulation of timing. Interestingly, the timing-dependent effects of post-exercise cold exposure on sleep may parallel with those observed following acute exercise. Strenuous exercise has been suggested to improve sleep when performed sufficiently before bedtime but may impair sleep if undertaken too close to bedtime, likely through alterations in thermoregulation, autonomic balance, and physiological arousal [18, 77]. As with strenuous exercise, post-exercise cold exposure may similarly act as an acute stressor whose net effect on sleep depends on its temporal proximity to habitual bedtime, operating through these shared thermoregulatory, autonomic, and arousal pathways.

4.2 Autonomic Function

4.2.1 Autonomic Function and Hormonal Regulation

Athletes routinely participate in demanding high-intensity, prolonged "threshold" training or competition, all of which can influence autonomic nervous system regulation, particularly the balance between sympathetic and parasympathetic activity during and following exercise [78]. Autonomic disruption resulting from high-load evening exercise has been linked to delayed sleep onset, reduced total sleep time, and lower sleep efficiency [18]. Such dysregulation is associated with elevated cortisol levels [62, 79] and increased sympathetic activity [55, 79], both of which heighten physiological arousal [80, 81] and impair the normal downregulation of human stress-response systems (e.g., hypothalamic–pituitary–adrenal and sympathetic–adrenal–medullary axes) necessary for healthy sleep function [82, 83].

4.2.2 Cold Exposure and Parasympathetic Activation

Research investigating cold exposure following exercise in both athletes (e.g., cold water immersion or cryotherapy)

and non-athletes has revealed that post-exercise cold exposure may enhance nocturnal sleep for two primary reasons: (i) via an increase in vagal tone and increased relaxation and (ii) via a reduction in cortisol, a basal stress hormone [84]. Eight studies have investigated the effects of post-exercise cold exposure on athletes' nighttime sleep by examining both nocturnal autonomic function (e.g., HRV) and sleep measures [22, 26–28, 31, 52, 53, 58]. Of these studies, two which utilized cold water immersion [27, 31] and three which utilized cryotherapy after training [22, 28, 52] reported increased vagal tone during the subsequent night and concurrently demonstrated improved sleep quantity and/or quality compared with control conditions (Table 1). Previous research has shown that post-exercise cold water immersion accelerates parasympathetic reactivation [37, 85] by increasing central blood volume, which in turn augments stroke volume and cardiac output [86, 87]. Consequently, these alterations have been shown to stimulate both arterial and cardiopulmonary baroreflexes, leading to a reduction in sympathetic activation and an increase in parasympathetic activity; this resulted in resting bradycardia [88] and reduced blood pressure and heart rate during sleep [89]. Additionally, cold exposure activates cold sensors in the skin, subcutaneous tissue, and veins which may enhance cardiac parasympathetic reactivation [85]. The aforementioned autonomic changes have likely been reflected in some, but not all, applied studies currently reviewed in which post-exercise cold exposure was conducted. Higher HRV values recorded during the night may explain the higher subjective sleep quality [31] and reduced arousal and limb movements, as well as higher SWS proportion, during subsequent sleep [27]. The latter could be attributable to the fact that under normal physiological conditions (i.e., normal, healthy, and undisturbed autonomic nervous system function), parasympathetic activity increases during SWS while sympathetic activity decreases [90]. Accordingly, the enhanced parasympathetic activity following post-exercise cold exposure, particularly cold water immersion, has been found to be associated with reduced muscle soreness and a reduced perception of fatigue (as described in the next section)—as well as greater perceptions of relaxation compared with passive rest [91, 92]—which may improve subsequent nocturnal sleep. The exact mechanism, however, behind the link between increased parasympathetic activity and reduced muscle soreness has not been elucidated yet. It should be noted, however, that although whole-body cryotherapy and cold-water immersion are both classified as cold recovery modalities, they differ markedly in their physiologic consequences—including heat-transfer characteristics, tissue cooling profiles, and cardiovascular responses. Specifically, cold-water immersion can produce more sustained muscle and core cooling depending on the protocol and provides hydrostatic effects that increase central blood volume and cardiac preload, whereas whole-body cryotherapy involves short-duration, cold air exposure without hydrostatic effects [93]. Further, cold-water immersion has been shown to lower skin temperature for several hours after exposure [30], whereas the cooling produced by cryotherapy dissipates more rapidly. Nevertheless, recent meta-analytic evidence suggests that both interventions elicit comparable increases in parasympathetic nervous system activity despite these physiological differences [94]. Only two studies [47, 51] have directly compared whole-body cryotherapy and cold-water immersion with respect to sleep-related outcomes. Qu et al. (2022) reported more favorable effects of whole-body cryotherapy on subjective sleep quality [47], whereas Haq et al. (2022) found no differences between the two modalities in sleep parameters using wrist-worn sleep trackers [51]. Consequently, mechanistic findings for one modality should not necessarily be extrapolated to the other and direct comparative studies remain limited.

4.2.3 Post-Exercise Thermal Interventions, Psychophysiological Stress, and Sleep

In addition to sympathetic hyperactivity, psychophysiological stress and/or anxiety may contribute to poor sleep [95]. In this regard, studies have reported that following demanding competition [79] or during intensified training camps, athletes demonstrate reduced sleep quantity [96] and quality along with higher psychophysiological stress, as indicated by an increased salivary cortisol concentration [62]. A previous study by Reed and colleagues (2023) demonstrated that cortisol concentrations were reduced after cold water immersion, with this effect lasting up to 3 h post-immersion [97]. Nonetheless, earlier [24] and more recent studies [49, 98] did not confirm the aforementioned findings. Ajjimaporn and colleagues (2019) investigated nine healthy individuals and found that neither cold showers (15 °C for 15 min) nor passive recovery (25 °C room temperature for 15 min) following exercise in the heat influenced salivary cortisol concentrations [98]. A study examining the effects of repeated post-resistance-exercise cold or hot water immersion on inflammatory indices in 18 academy rugby players revealed that water immersion, irrespective of water temperature, reduced creatine kinase concentrations compared with control conditions. However, cortisol concentration did not differ significantly between interventions [99]. The lack of significant differences in cortisol responses may be attributed to the high inter- and intraindividual variability often observed in cortisol measurements. Finally, none of the above studies measured sleep.

The current literature indicates that post-exercise cold exposure, particularly cold water immersion, may increase subjective recovery primarily through autonomic

modulation. However, the effects on physiological markers including cortisol and creatine kinase concentrations are inconsistent. Given the mixed findings, further research is necessary to elucidate the precise mechanisms under which post-exercise cold exposure or warm/heat therapy influences hormonal and inflammatory responses that modulate sleep.

4.3 Muscle Soreness/Pain

Several studies in individual and team-sports athletes have shown that intense and prolonged exercise can induce inflammation and muscle soreness, which may persist 2–3 days after the conclusion of exercise [100]. These symptoms have been associated with sleep disturbances, as muscle soreness has been proposed to promote increased movement during sleep in an attempt to maintain comfort [101, 102].

4.3.1 Post-Exercise Cold Therapy, Muscle Soreness, and Sleep

Post-exercise cold exposure, whether through CWI or cryotherapy, has been shown in some studies to improve subsequent sleep [103], potentially due to an analgesic effect [104]. Most plausibly, the increased perception of recovery and reduced muscle soreness was a primary reason for improvement in sleep following post-exercise cold exposure. Supporting this improved perception, leg immersion in cold water or WBC after training decreased total serum creatine kinase concentration—an indicator of muscle damage—in high-level rugby players in comparison with passive recovery [40, 105]. This suggests that cold exposure enhanced recovery from muscle damage by reducing cell membrane breakdown or increased cell permeability caused by oxidant agents produced during physical exercise [106]. Moreover, Qu and colleagues (2022) found that runners who underwent a muscle-damaging exercise protocol including running and unaccustomed jump exercises followed by WBC had reduced inflammatory markers (lactate dehydrogenase and interleukin-6) and improved subjective sleep quality compared with the passive recovery condition [47]. In the same study, however, the positive effects of cold exposure were not verified after cold water immersion, as subjective sleep measures remained unchanged. Similarly, findings from the study by Tabben and colleagues (2018) indicated that post-exercise cold-water immersion improved sleep quality and increased perception of recovery despite unaffected muscle damage markers [49].

4.4 Methodological Limitations

There are some methodological limitations with regard to the interpretation of literature findings that should be acknowledged. First, the current literature is heterogeneous regarding study populations, which include elite athletes, well-trained and recreationally trained individuals, and non-athlete participants. Therefore, caution is warranted when generalizing these findings across populations, and future research should directly examine whether training status and competitive level modify the effects of post-exercise thermal interventions on sleep.

In addition, the studies included in this review employed diverse methodologies to assess sleep, including polysomnography, actigraphy, subjective questionnaires, and movement-based indices. These approaches differ substantially in their validity and sensitivity. Polysomnography is considered the gold standard for quantifying sleep architecture [107, 108], whereas actigraphy primarily estimates sleep–wake behavior [109] and does not characterize sleep stages. Likewise, subjective sleep assessment relies on questionnaires and sleep diaries, which are cost-effective but highly susceptible to response bias, compliance issues, and participant burden [110]. Therefore, findings derived from actigraphy or self-reported outcomes should be interpreted with caution, particularly in the absence of polysomnographic confirmation. This methodological heterogeneity likely contributes to the variability in reported effects of post-exercise thermal interventions on sleep and underscores the need for future studies employing standardized and comprehensive sleep assessment protocols.

5 Conclusions

Current research suggests that thermal post-exercise interventions may differentially influence subsequent sleep in athletes through multiple interacting mechanisms, including thermoregulation, autonomic modulation, and effects on muscle soreness. The effectiveness of post-exercise cold interventions on subsequent nighttime sleep is likely dependent on the timing of exposure relative to the athlete's circadian phase. If applied too close to habitual bedtime (< 2 h), cold exposure may disrupt thermal gradients, potentially impairing sleep initiation and continuity. Post-exercise cold interventions applied at the appropriate timing before bedtime (i.e., > 2 h) may however improve sleep quality via increased parasympathetic activity and/or reduced perceived muscle soreness and therefore lower somatic movement during sleep. Conversely, post-exercise heat interventions applied before sleep or cooling interventions during sleep using high-heat-capacity mattresses may facilitate sleep by enhancing peripheral vasodilation and promoting

distal-to-proximal skin temperature gradients in line with endogenous circadian rhythms.

As athletes are often vulnerable to sleep loss [111], identifying effective, individualized strategies for sleep optimization is important for enhancing recovery, health, and performance. However, the impact of post-exercise thermal interventions on sleep characteristics of athletes and active individuals remains inconsistent primarily due to methodological heterogeneity. To clarify the role of post-exercise thermal therapies in optimizing athletes' sleep, standardized protocols and consideration of moderating variables, such as sex, time of the day, environmental temperature, acclimatization status, and training load are necessary.

5.1 Summary Statement

Post-exercise thermal interventions may modulate nocturnal sleep, with effects dependent on timing, temperature, and environmental context. Changes in the DPG regulate sleep onset. Cold water immersion too close to bedtime (<2 h) may impact DPG and delay sleep, while earlier application (≥ 4 h) supports recovery without disrupting thermoregulation. These timing effects should be regarded as a hypothesis and require direct experimental confirmation. Heat exposure prior to sleep or body cooling during sleep may enhance DPG and improve both sleep onset and quality.

5.2 Future Directions

Future research should determine optimal timing and dose of post-exercise thermal interventions for sleep enhancement. Differences in sex, individual thermoregulatory profiles, and long-term effects of repeated thermal recovery interventions on sleep are dynamic domains of research requiring thorough investigation. Real-world field studies using wearable sleep and thermoregulation monitors are warranted to validate laboratory findings.

Author Contributions PGB, SLH, and PGM conceived the idea for this review. PGM, SLH, TM, JL, AGT, and PGB contributed to the design and conceptual development of the review. PGM and PGB conducted the literature search. PGM, AGT, and PGB prepared the first draft of the manuscript. SLH, TM, and JL revised the original manuscript. All authors have read and approved the final version.

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

Data Availability No datasets were generated or analyzed during the current study.

Declarations

Conflicts of Interest The authors declare that they have no competing interests relevant to the content of this review. Shona Halson and Toby Mündel are Editorial Board members of *Sports Medicine* but were not involved in the selection of peer reviewers for this manuscript or any of the subsequent editorial decisions.

Ethics Approval Not applicable.

Consent to Participate Not applicable.

Consent for Publication Not applicable.

References

1. Mah CD, Mah KE, Kezirian EJ, Dement WC. The effects of sleep extension on the athletic performance of collegiate basketball players. Sleep. 2011;34(7):943–50.
2. Walsh NP, Halson SL, Sargent C, Roach GD, Nedelec M, Gupta L, et al. Sleep and the athlete: narrative review and 2021 expert consensus recommendations. Br J Sports Med. 2021. https://doi.org/10.1136/bjsports-2020-102025.
3. Sargent C, Lastella M, Halson SL, Roach GD. How much sleep does an elite athlete need? Int J Sports Physiol Perform. 2021;16(12):1746–57.
4. Sargent C, Halson S, Roach GD. Sleep or swim? Early-morning training severely restricts the amount of sleep obtained by elite swimmers. Eur J Sport Sci. 2014;14(Suppl 1):S310–5.
5. Koutouvakis NG, Geladas ND, Mouratidis A, Toubekis AG, Botonis PG. Habitual nocturnal sleep, napping behavior, and recovery following training and competition in elite water polo: sex-related effects. Int J Sports Physiol Perform. 2024;19(7):651–60.
6. Sim JE, Leota J, Mascaro L, Hoffman D, Facer-Childs ER. Sleep patterns before and after competition: a real-world examination of elite athletes. J Sports Sci. 2023;41(22):2014–26.
7. Vaile J, Halson S, Gill N, Dawson B. Effect of hydrotherapy on the signs and symptoms of delayed onset muscle soreness. Eur J Appl Physiol. 2008;102(4):447–55.
8. Sargent C, Lastella M, Halson SL, Roach GD. The impact of training schedules on the sleep and fatigue of elite athletes. Chronobiol Int. 2014;31(10):1160–8.
9. Lastella M, Roach GD, Halson SL, Martin DT, West NP, Sargent C. Sleep/wake behaviour of endurance cyclists before and during competition. J Sports Sci. 2015;33(3):293–9.
10. Troynikov O, Watson CG, Nawaz N. Sleep environments and sleep physiology: a review. J Therm Biol. 2018;78:192–203.
11. Van Someren EJ. Mechanisms and functions of coupling between sleep and temperature rhythms. Prog Brain Res. 2006;153:309–24.
12. Krauchi K, Cajochen C, Pache M, Flammer J, Wirz-Justice A. Thermoregulatory effects of melatonin in relation to sleepiness. Chronobiol Int. 2006;23(1–2):475–84.
13. Lack LC, Wright HR. Chronobiology of sleep in humans. Cell Mol Life Sci. 2007;64(10):1205–15.
14. Henderson MJ, Grandou C, Chrismas BCR, Coutts AJ, Impellizzeri FM, Taylor L. Core body temperatures in intermittent sports: a systematic review. Sports Med. 2023;53(11):2147–70.
15. Krauchi K. The thermophysiological cascade leading to sleep initiation in relation to phase of entrainment. Sleep Med Rev. 2007;11(6):439–51.
16. Krauchi K. The human sleep-wake cycle reconsidered from a thermoregulatory point of view. Physiol Behav. 2007;90(2–3):236–45.
17. Roberts SSH, Teo WP, Warmington SA. Effects of training and competition on the sleep of elite athletes: a systematic review and meta-analysis. Br J Sports Med. 2019;53(8):513–22.

18. Leota J, Presby DM, Le F, Czeisler ME, Mascaro L, Capodilupo ER, et al. Dose-response relationship between evening exercise and sleep. Nat Commun. 2025;16(1):3297.
19. Togo F, Aizawa S, Arai J, Yoshikawa S, Ishiwata T, Shephard RJ, et al. Influence on human sleep patterns of lowering and delaying the minimum core body temperature by slow changes in the thermal environment. Sleep. 2007;30(6):797–802.
20. Krauchi K, Fattori E, Giordano A, Falbo M, Iadarola A, Agli F, et al. Sleep on a high heat capacity mattress increases conductive body heat loss and slow wave sleep. Physiol Behav. 2018;185:23–30.
21. Horgan BG, Halson SL, Drinkwater EJ, West NP, Tee N, Alcock RD, et al. No effect of repeated post-resistance exercise cold or hot water immersion on in-season body composition and performance responses in academy rugby players: a randomised controlled cross-over design. Eur J Appl Physiol. 2023;123(2):351–9.
22. Aloulou A, Leduc C, Duforez F, Piscione J, Cheradame J, Bieuzen F, et al. Effect of an innovative mattress and cryotherapy on sleep after an elite rugby match. Med Sci Sports Exerc. 2020;52(12):2655–62.
23. Chauvineau M, Pasquier F, Poirier C, Le Garrec S, Duforez F, Guilhem G, et al. Higher training loads affect sleep in endurance runners: can a high-heat-capacity mattress topper mitigate negative effects? J Sports Sci. 2023;41(17):1605–16.
24. Halson SL, Quod MJ, Martin DT, Gardner AS, Ebert TR, Laursen PB. Physiological responses to cold water immersion following cycling in the heat. Int J Sports Physiol Perform. 2008;3(3):331–46.
25. Vaile J, Halson S, Gill N, Dawson B. Effect of hydrotherapy on recovery from fatigue. Int J Sports Med. 2008;29(7):539–44.
26. Douzi W, Dupuy O, Theurot D, Boucard G, Dugue B. Partial-body cryostimulation after training improves sleep quality in professional soccer players. BMC Res Notes. 2019;12(1):141.
27. Chauvineau M, Pasquier F, Guyot V, Aloulou A, Nedelec M. Effect of the depth of cold water immersion on sleep architecture and recovery among well-trained male endurance runners. Front Sports Act Living. 2021;3:659990.
28. Arc-Chagnaud C, Dugue B, Bouzigon R, Pla R, Bosquet L, Consortium Dd, et al. The effectiveness of cryostimulation exposure on sleep and recovery in male athletes: timing considerations. Eur J Sport Sci. 2024;24(12):1788–97.
29. Chauvineau M, Pasquier F, Duforez F, Guilhem G, Nedelec M. Increased training load promotes sleep propensity and slow-wave sleep in endurance runners: can a high-heat-capacity mattress topper modulate this effect? J Sleep Res. 2024;33(4):e14132.
30. Robey E, Dawson B, Halson S, Gregson W, King S, Goodman C, et al. Effect of evening postexercise cold water immersion on subsequent sleep. Med Sci Sports Exerc. 2013;45(7):1394–402.
31. Al Haddad H, Parouty J, Buchheit M. Effect of daily cold water immersion on heart rate variability and subjective ratings of well-being in highly trained swimmers. Int J Sports Physiol Perform. 2012;7(1):33–8.
32. Uchida S, Shioda K, Morita Y, Kubota C, Ganeko M, Takeda N. Exercise effects on sleep physiology. Front Neurol. 2012;3:48.
33. Aloulou A, Duforez F, Bieuzen F, Nedelec M. The effect of night-time exercise on sleep architecture among well-trained male endurance runners. J Sleep Res. 2020;29(6):e12964.
34. Nedelec M, Halson S, Delecroix B, Abaidia AE, Ahmaidi S, Dupont G. Sleep hygiene and recovery strategies in elite soccer players. Sports Med. 2015;45(11):1547–59.
35. Bouzigon E, Ravier G, Dugue B, Grapper F. The use of whole-body cryostimulation to improve the quality of sleep in athletes during high level standard competitions. Br J Sports Med. 2014;48:572.
36. Araujo CG, Scharhag J. Athlete: a working definition for medical and health sciences research. Scand J Med Sci Sports. 2016;26(1):4–7.
37. Ihsan M, Watson G, Abbiss CR. What are the physiological mechanisms for post-exercise cold water immersion in the recovery from prolonged endurance and intermittent exercise? Sports Med. 2016;46(8):1095–109.
38. Bouzigon R, Dupuy O, Tiemessen I, De Nardi M, Bernard JP, Mihailovic T, et al. Cryostimulation for post-exercise recovery in athletes: a consensus and position paper. Front Sports Act Living. 2021;3:688828.
39. Moore E, Fuller JT, Bellenger CR, Saunders S, Halson SL, Broatch JR, et al. Effects of cold-water immersion compared with other recovery modalities on athletic performance following acute strenuous exercise in physically active participants: a systematic review, meta-analysis, and meta-regression. Sports Med. 2023;53(3):687–705.
40. Banfi G, Lombardi G, Colombini A, Melegati G. Whole-body cryotherapy in athletes. Sports Med. 2010;40(6):509–17.
41. Schaal K, Le Meur Y, Bieuzen F, Petit O, Hellard P, Toussaint JF, et al. Effect of recovery mode on postexercise vagal reactivation in elite synchronized swimmers. Appl Physiol Nutr Metab. 2013;38(2):126–33.
42. Skein M, Wingfield G, Gale R, Washington TL, Minett GM. Sleep quantity and quality during consecutive day heat training with the inclusion of cold-water immersion recovery. J Therm Biol. 2018;74:63–70.
43. Alexander J, Carling C, Rhodes D. Utilisation of performance markers to establish the effectiveness of cold-water immersion as a recovery modality in elite football. Biol Sport. 2022;39(1):19–29.
44. Halson SL, Bartram J, West N, Stephens J, Argus CK, Driller MW, et al. Does hydrotherapy help or hinder adaptation to training in competitive cyclists? Med Sci Sports Exerc. 2014;46(8):1631–9.
45. Lastella M, Roach GD, Halson SL, Sargent C. The effects of cold water immersion on the amount and quality of sleep obtained by elite cyclists during a simulated hill climbing tour. Sport Sci Health. 2019;15:223–8.
46. Horgan BG, Tee N, West NP, Drinkwater EJ, Halson SL, Colomer CME, et al. Acute performance, daily well-being, and hormone responses to water immersion after resistance exercise in junior international and subelite male volleyball athletes. J Strength Cond Res. 2023;37(8):1643–53.
47. Qu C, Wu Z, Xu M, Lorenzo S, Dong Y, Wang Z, et al. Cryotherapy on subjective sleep quality, muscle, and inflammatory response in Chinese middle- and long-distance runners after muscle damage. J Strength Cond Res. 2022;36(10):2883–90.
48. Robey E, Dawson B, Halson S, Gregson W, Goodman C, Eastwood P. Sleep quantity and quality in elite youth soccer players: a pilot study. Eur J Sport Sci. 2014;14(5):410–7.
49. Tabben M, Ihsan M, Ghoul N, Coquart J, Chaouachi A, Chaabene H, et al. Cold water immersion enhanced athletes' wellness and 10-m short sprint performance 24-h after a simulated mixed martial arts combat. Front Physiol. 2018;9:1542.
50. Krueger M, Costello JT, Stenzel M, Mester J, Wahl P. The physiological effects of daily cold-water immersion on 5-day tournament performance in international standard youth field-hockey players. Eur J Appl Physiol. 2020;120(1):295–305.
51. Haq A, Ribbans WJ, Hohenauer E, Baross AW. The comparative effect of different timings of whole body cryotherapy treatment with cold water immersion for post-exercise recovery. Front Sports Act Living. 2022;4:940516.
52. Douzi W, Dupuy O, Tanneau M, Boucard G, Bouzigon R, Dugue B. 3-min whole body cryotherapy/cryostimulation after

training in the evening improves sleep quality in physically active men. Eur J Sport Sci. 2019;19(6):860–7.
53. Mihailovic T, Groslambert A, Bouzigon R, Feaud S, Millet GP, Gimenez P. Acute responses to repeated-sprint training in hypoxia combined with whole-body cryotherapy: a preliminary study. Int J Sports Physiol Perform. 2024;19(3):280–9.
54. Malone JJ, Hodges D, Roberts C, Sinclair JK, Page RM, Allan R. Effect of alterations in whole-body cryotherapy (WBC) exposure on post-match recovery markers in elite Premier League soccer players. Biol Sport. 2022;39(1):31–6.
55. Schaal K, Le Meur Y, Louis J, Filliard JR, Hellard P, Casazza G, et al. Whole-body cryostimulation limits overreaching in elite synchronized swimmers. Med Sci Sports Exerc. 2015;47(7):1416–25.
56. Grainger A, Comfort P, Heffernan S. No effect of partial-body cryotherapy on restoration of countermovement jump or well-being performance in elite Rugby Union players during the competitive phase of the season. Int J Sports Physiol Perform. 2020;15(1):98–104.
57. Kim TJ, Ha KH, Park TY, Kim JH, Lee JM, Jung HC. Effects of partial-body cryotherapy on athletic performance and sleep quality in division I collegiate basketball athletes. J Hum Kinet. 2025;96(Spec Issue):187–99.
58. Arc-Chagnaud C, Dugue B, Pla R, Bouzigon R, Bosquet L, D-Day C, et al. Effects of repeated cryostimulation exposures on sleep quality in swimmers during an intense training period. Exp Physiol. 2025. https://doi.org/10.1113/EP092293.
59. Schaal K, Y LEM, Louis J, Filliard JR, Hellard P, Casazza G, et al. Whole-body cryostimulation limits overreaching in elite synchronized swimmers. Med Sci Sports Exerc. 2015 Jul;47(7):1416–25.
60. Frauscher B, Gabelia D, Mitterling T, Biermayr M, Bregler D, Ehrmann L, et al. Motor events during healthy sleep: a quantitative polysomnographic study. Sleep. 2014;37(4):763–73, 73A-73B.
61. Hausswirth C, Louis J, Aubry A, Bonnet G, Duffield R, Y LEM. Evidence of disturbed sleep and increased illness in overreached endurance athletes. Med Sci Sports Exerc. 2014;46(5):1036–45.
62. Botonis PG, Toubekis AG. Intensified Olympic preparation: sleep and training-related hormonal and immune responses in water polo. Int J Sports Physiol Perform. 2023;18(2):187–94.
63. Haghayegh S, Khoshnevis S, Smolensky MH, Diller KR, Castriotta RJ. Before-bedtime passive body heating by warm shower or bath to improve sleep: a systematic review and meta-analysis. Sleep Med Rev. 2019;46:124–35.
64. Whitworth-Turner C, Di Michele R, Muir I, Gregson W, Drust B. A shower before bedtime may improve the sleep onset latency of youth soccer players. Eur J Sport Sci. 2017;17(9):1119–28.
65. Ahokas EK, Ihalainen JK, Hanstock HG, Savolainen E, Kyröläinen H. A post-exercise infrared sauna session improves recovery of neuromuscular performance and muscle soreness after resistance exercise training. Biol Sport. 2023;40(3):681–9.
66. Krauchi K, Cajochen C, Werth E, Wirz-Justice A. Functional link between distal vasodilation and sleep-onset latency? Am J Physiol Regul Integr Comp Physiol. 2000;278(3):R741–8.
67. Stevenson S, Suppiah H, Mundel T, Driller M. Under the covers: the effect of a temperature-controlled mattress cover on sleep and perceptual measures in healthy adults. Clocks Sleep. 2025. https://doi.org/10.3390/clockssleep7040055.
68. Moyen NE, Ediger TR, Taylor KM, Hancock EG, Holden LD, Tracy EE, et al. Sleeping for one week on a temperature-controlled mattress cover improves sleep and cardiovascular recovery. Bioengineering. 2024. https://doi.org/10.3390/bioengineering11040352.
69. Campbell SS, Broughton RJ. Rapid decline in body temperature before sleep: fluffing the physiological pillow? Chronobiol Int. 1994;11(2):126–31.
70. Van Someren EJ. More than a marker: interaction between the circadian regulation of temperature and sleep, age-related changes, and treatment possibilities. Chronobiol Int. 2000;17(3):313–54.
71. Krauchi K, Wirz-Justice A. Circadian rhythm of heat production, heart rate, and skin and core temperature under unmasking conditions in men. Am J Physiol. 1994;267(3 Pt 2):R819–29.
72. Krauchi K, Deboer T. The interrelationship between sleep regulation and thermoregulation. Front Biosci (Landmark Ed). 2010;15(2):604–25.
73. Raymann RJ, Swaab DF, Van Someren EJ. Cutaneous warming promotes sleep onset. Am J Physiol Regul Integr Comp Physiol. 2005;288(6):R1589–97.
74. Herberger S, Penzel T, Fietze I, Glos M, Cicolin A, Fattori E, et al. Enhanced conductive body heat loss during sleep increases slow-wave sleep and calms the heart. Sci Rep. 2024;14(1):4669.
75. Botonis PG, Kounalakis SN, Cherouveim ED, Koskolou MD, Geladas ND. Effects of menthol application on the skin during prolonged immersion in cool and cold water. Scand J Med Sci Sports. 2018;28(3):1193–200.
76. Robey E, Dawson B, Halson S, Goodman C, Gregson W, Eastwood P. Post-exercise cold water immersion: effect on core temperature and melatonin responses. Eur J Appl Physiol. 2013;113(2):305–11.
77. Korkutata A, Korkutata M, Lazarus M. The impact of exercise on sleep and sleep disorders. NPJ Biol Timing Sleep. 2025 Feb 3;2(1).
78. Holt AC, Plews DJ, Oberlin-Brown KT, Merien F, Kilding AE. Cardiac parasympathetic and anaerobic performance recovery after high-intensity exercise in rowers. Int J Sports Physiol Perform. 2019;14(3):331–8.
79. O'Donnell S, Bird S, Jacobson G, Driller M. Sleep and stress hormone responses to training and competition in elite female athletes. Eur J Sport Sci. 2018;18(5):611–8.
80. Bonnet MH, Arand DL. Hyperarousal and insomnia: state of the science. Sleep Med Rev. 2010;14(1):9–15.
81. Moldofsky H. Sleep and pain. Sleep Med Rev. 2001;5(5):385–96.
82. Burgess HJ, Trinder J, Kim Y, Luke D. Sleep and circadian influences on cardiac autonomic nervous system activity. Am J Physiol. 1997;273(4):H1761–8.
83. Buckley TM, Schatzberg AF. On the interactions of the hypothalamic-pituitary-adrenal (HPA) axis and sleep: normal HPA axis activity and circadian rhythm, exemplary sleep disorders. J Clin Endocrinol Metab. 2005;90(5):3106–14.
84. Charmandari E, Tsigos C, Chrousos G. Endocrinology of the stress response. Annu Rev Physiol. 2005;67:259–84.
85. Buchheit M, Peiffer JJ, Abbiss CR, Laursen PB. Effect of cold water immersion on postexercise parasympathetic reactivation. Am J Physiol Heart Circ Physiol. 2009;296(2):H421–7.
86. Park KS, Choi JK, Park YS. Cardiovascular regulation during water immersion. Appl Human Sci. 1999;18(6):233–41.
87. Gabrielsen A, Johansen LB, Norsk P. Central cardiovascular pressures during graded water immersion in humans. J Appl Physiol (1985). 1985;75(2):581–5.
88. Pump B, Shiraishi M, Gabrielsen A, Bie P, Christensen NJ, Norsk P. Cardiovascular effects of static carotid baroreceptor stimulation during water immersion in humans. Am J Physiol Heart Circ Physiol. 2001;280(6):H2607–15.
89. Nagura S, Sakagami T, Kakiichi A, Yoshimoto M, Miki K. Acute shifts in baroreflex control of renal sympathetic nerve activity induced by REM sleep and grooming in rats. J Physiol. 2004;558(Pt 3):975–83.
90. Zoccoli G, Amici R. Sleep and autonomic nervous system. Curr Opin Physiol. 2020;15:128–33.

91. Stanley J, Buchheit M, Peake JM. The effect of post-exercise hydrotherapy on subsequent exercise performance and heart rate variability. Eur J Appl Physiol. 2012;112(3):951–61.
92. Stanley J, Peake JM, Buchheit M. Consecutive days of cold water immersion: effects on cycling performance and heart rate variability. Eur J Appl Physiol. 2013;113(2):371–84.
93. White GE, Wells GD. Cold-water immersion and other forms of cryotherapy: physiological changes potentially affecting recovery from high-intensity exercise. Extrem Physiol Med. 2013;2(1):26.
94. Jdidi H, Dugue B, de Bisschop C, Dupuy O, Douzi W. The effects of cold exposure (cold water immersion, whole- and partial- body cryostimulation) on cardiovascular and cardiac autonomic control responses in healthy individuals: a systematic review, meta-analysis and meta-regression. J Therm Biol. 2024;121:103857.
95. Juliff LE, Halson SL, Peiffer JJ. Understanding sleep disturbance in athletes prior to important competitions. J Sci Med Sport. 2015;18(1):13–8.
96. Serpell BG, Horgan BG, Colomer CME, Field B, Halson SL, Cook CJ. Sleep and salivary testosterone and cortisol during a short preseason camp: a study in professional Rugby Union. Int J Sports Physiol Perform. 2019;14(6):796–804.
97. Reed EL, Chapman CL, Whittman EK, Park TE, Larson EA, Kaiser BW, et al. Cardiovascular and mood responses to an acute bout of cold water immersion. J Therm Biol. 2023;118:103727.
98. Ajjimaporn A, Chaunchaiyakul R, Pitsamai S, Widjaja W. Effect of cold shower on recovery from high-intensity cycling in the heat. J Strength Cond Res. 2019;33(8):2233–40.
99. Horgan BG, West NP, Tee N, Halson SL, Drinkwater EJ, Chapman DW, et al. Effect of repeated post-resistance exercise cold or hot water immersion on in-season inflammatory responses in academy rugby players: a randomised controlled cross-over design. Eur J Appl Physiol. 2024;124(9):2615–28.
100. Doeven SH, Brink MS, Kosse SJ, Lemmink K. Postmatch recovery of physical performance and biochemical markers in team ball sports: a systematic review. BMJ Open Sport Exerc Med. 2018;4(1):e000264.
101. Taylor SR, Rogers GG, Driver HS. Effects of training volume on sleep, psychological, and selected physiological profiles of elite female swimmers. Med Sci Sports Exerc. 1997;29(5):688–93.
102. Sargent C, Lastella M, Halson SL, Roach GD. The validity of activity monitors for measuring sleep in elite athletes. J Sci Med Sport. 2016;19(10):848–53.
103. Dupuy O, Douzi W, Theurot D, Bosquet L, Dugue B. An evidence-based approach for choosing post-exercise recovery techniques to reduce markers of muscle damage, soreness, fatigue, and inflammation: a systematic review with meta-analysis. Front Physiol. 2018;9:403.
104. Hausswirth C, Louis J, Bieuzen F, Pournot H, Fournier J, Filliard JR, et al. Effects of whole-body cryotherapy vs. far-infrared vs. passive modalities on recovery from exercise-induced muscle damage in highly-trained runners. PLoS ONE. 2011;6(12):e27749.
105. Banfi G, Melegati G, Barassi A, Dogliotti G, Melzi d'Eril G, Dugue B, et al. Effects of whole-body cryotherapy on serum mediators of inflammation and serum muscle enzymes in athletes. J Therm Biol. 2009;34(2):55–9.
106. Banfi G, Melegati G, Valentini P. Effects of cold-water immersion of legs after training session on serum creatine kinase concentrations in rugby players. Br J Sports Med. 2007;41(5):339.
107. Lim DC, Mazzotti DR, Sutherland K, Mindel JW, Kim J, Cistulli PA, et al. Reinventing polysomnography in the age of precision medicine. Sleep Med Rev. 2020;52:101313.
108. Vlahoyiannis A, Sakkas GK, Manconi M, Aphamis G, Giannaki CD. A critical review on sleep assessment methodologies in athletic populations: factors to be considered. Sleep Med. 2020;74:211–23.
109. Agostinho M, Borges M, Pereira T, Borges DF, Soares JI. Are wearable sleep-tracking devices reliable alternatives to polysomnography? A systematic review and meta-Analysis. Behav Sleep Med. 2026;22:1–13.
110. Sadeh A. III. Sleep assessment methods. Monogr Soc Res Child Dev. 2015;80(1):33–48.
111. Botonis PG, Grammenou M, Toubekis AG. Athletes and sleep issues: new insights into translating laboratory findings in a real-world setting. Sports Health. 2025;17(3):435–7.

Springer Nature or its licensor (e.g. a society or other partner) holds exclusive rights to this article under a publishing agreement with the author(s) or other rightsholder(s); author self-archiving of the accepted manuscript version of this article is solely governed by the terms of such publishing agreement and applicable law.

Authors and Affiliations

Panagiotis G. Miliotis[1] · Shona L. Halson[2,3] · Toby Mundel[4] · Josh Leota[5,6,7] · Argyris G. Toubekis[1,8] · Petros G. Botonis[1,8]

✉ Petros G. Botonis
pboton@phed.uoa.gr

1 School of Physical Education and Sport Science, National and Kapodistrian University of Athens, 41, Ethnikis Antistaseos, 17237 Dafne, Greece

2 School of Behavioural and Health Sciences, Australian Catholic University, Brisbane, QLD, Australia

3 Sports Performance, Recovery, Injury and New Technologies (SPRINT) Research Centre, Australian Catholic University, Brisbane, QLD, Australia

4 Department of Kinesiology, Brock University, St Catharines, ON, Canada

5 Sleep and Circadian Rhythms Research Program, School of Psychological Sciences, Faculty of Medicine, Nursing and Health Sciences, Monash University, Melbourne, Australia

6 Division of Sleep and Circadian Disorders, Departments of Medicine and Neurology, Brigham and Women's Hospital, Boston, USA

7 Department of Research, Algorithms, and Data Science, WHOOP Inc, Boston, MA, USA

8 Institute for Sports Performance, Biorhythms and Environment, National and Kapodistrian University of Athens, Athens, Greece