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The effectiveness of cryostimulation exposure on sleep and recovery in male athletes: Timing considerations

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Abstract

The objectives of the study were (i) to evaluate the effects of whole-body cryostimulation (WBC) after training as an effective tool to improve sleep and recovery and (ii) to determine which exposure schedule for WBC (immediately after training vs. 1h before bedtime) is the most appropriate to improve sleep and recovery. Twenty-two well-trained male athletes or triathletes (23.1 ± 3.5 -years) were recruited in this controlled crossover protocol. Each participant completed the three experimental sessions, each composed of a running training session and one night of sleep analysis. Depending on the experimental condition, subjects were exposed—or not (CONT)—to WBC immediately after training (CRYO 7 p.m.) or 1h before going to bed (CRYO 10 p.m.). All participants were randomly assigned to each condition, spaced seven days apart. Sleep was monitored via actimetry, cerebral activity recordings, heart rate variability, body core temperature, and perceptual measurements. WBC after training did not modify subjective or objective sleep parameters compared to the control condition. However, WBC significantly improved cardiac parasympathetic activity. More specifically, it was more activated during the night following the CRYO 10 p.m. condition than in the other experimental conditions. Core body temperature (CBT) 1h after bedtime was the lowest in the CRYO 10 p.m. condition. This study confirmed the effectiveness of WBC as a recovery technique after intense evening training. We suggest that WBC may exhibit the most significant benefit on recovery if the session is performed 1h before bedtime, acting on subsequent parasympathetic activation and CBT drop.

KEYWORDS

actigraphy, parasympathetic activity, polysomnography, sleep, whole-body cryostimulation, whole-body cryotherapy

D-DAY consortium members (See [Appendix](#)).

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Highlights

- Cryotherapy improves sleep through better parasympathetic activation.
- Time of exposure affects sleep parameters differently.
- An exposure to cryostimulation close to sleep (at 10 p.m.) improves parasympathetic activation even more than an exposure just after training (at 7 p.m.).
- An exposure to cryostimulation close to sleep (at 10 p.m.) decreases the internal temperature to a greater extent than an exposure just after training (at 7 p.m.).

1 | INTRODUCTION

Achieving a high level of physical performance requires regular training with increasing and more intense training loads. However, without control of the athlete's recovery processes, training load alone does not guarantee the highest level of performance. Recovery is considered a key factor in the training process, enabling adaptation to training while avoiding the risk of overload injuries and nonfunctional overreaching (Kellmann et al., 2018; Soligard et al., 2016). Many authors consider that nutrition and sleep are basic to recovery (Doherty et al., 2019; Halson, 2014). However, with increased training loads, the resting time between two training sessions may be too short. Therefore, combining nutrition and sleep-based interventions with other techniques is necessary (Doherty et al., 2019).

More specifically, scientific research has investigated whether several recovery techniques effectively influence sleep quality or quantity. Among these practices, cold therapies have demonstrated their effectiveness in athletes (Chauvineau et al., 2021; Douzi, Dupuy, Tanneau, et al., 2019; Douzi, Dupuy, Theurot, et al., 2019; Schaal et al., 2015). One of these interventions is whole-body cryostimulation (WBC), which consists of whole-body exposure to dry air at the cryogenic temperature (between -50 and -195°C), and is becoming quite commonly used as a recovery strategy by high-level athletes (Bouzigon et al., 2021; Moore et al., 2023). Indeed, WBC has been found to lead to numerous valuable physiological effects. It produces analgesic effects, improves well-being, and reduces inflammation and muscle damage (Bouzigon et al., 2021; Dupuy et al., 2018). Moreover, previous studies have demonstrated that an acute WBC session can activate cardiac parasympathetic control of the autonomic nervous system (Louis et al., 2020; Theurot et al., 2021), which can be viewed as a marker of recovery (Kellmann et al., 2018). Furthermore, cryotherapy also influences the decrease of body temperature (Chauvineau et al., 2021), which is now known to initiate sleep and is associated with improved deep slow-wave sleep (SWS) quality (Herberger et al., 2024). In this athlete's recovery, WBC through all these mechanisms, may help to prevent the detrimental effects of intense training sessions and improve recovery of physical performance (Bouzigon et al., 2021; Moore et al., 2023; Wilson et al., 2019). Indeed, intense exercises increase the core body temperature (CBT) and sympathetic nervous system (SNS) activation and induce muscle soreness, which in turn can potentially affect sleep

quality and, consequently, recovery processes (Aloulou, Leduc, et al., 2020). Especially, intense exercise in the evening can lead to changes in sleep architecture, such as a decrease in rapid eye movement (REM) sleep (Frimpong et al., 2021), associated with alterations in circadian cycles (Kim et al., 2023), internal temperature (Aloulou, Duforez, et al., 2020; Miller et al., 2020), and autonomic regulation of the myocardium (Hani et al., 2009; Myllymaki et al., 2011), which can potentially affect sleep quality and, consequently, recovery processes.

For all these physiological benefits, cooling techniques, particularly WBC, have been suggested as methods that may positively impact sleep. Our group previously showed that WBC exposure after training improved healthy athletes' perceived sleep quality and quantity (Douzi, Dupuy, Tanneau, et al., 2019; Douzi, Dupuy, Theurot, et al., 2019). Moreover, in the context of an intensified training period, it has been shown that daily WBC could preserve sleep quantity and prevent increased perceived fatigue (Schaal et al., 2015). Moreover, a study by Chauvineau et al. (2021), using cold-water immersion (CWI), described cooling strategies as a tool to improve sleep by reducing CBT. Their results revealed a significant decrease in CBT after whole-body CWI and this effect was observed up to 80 min after exposure. Whole-body cooling was also associated with reduced arousal and limb movements the following night. However, the effect of WBC on sleep remains to be validated with accurate sleep measurement techniques and the current results remain contradictory (Aloulou, Leduc, et al., 2020).

To optimize athletes' recovery strategies, it is crucial to identify the appropriate timing of interventions with respect to training sessions. Most studies investigating cooling methods in athletes have focused on interventions that occur immediately after exercise sessions or as early as possible within 30 min. Therefore, it would appear worthwhile to investigate whether cold exposure closer to bedtime can further benefit athletes by modulating the CBT in view of enhancing sleep quality. A decrease in CBT may be an effective means of reducing sleep latency and promoting more profound and more restful sleep (Herberger et al., 2024).

The aim of this study was to determine the optimal timing of WBC exposure (immediately after training vs. 1h before bedtime) to enhance sleep and recovery in well-trained athletes. Based on evidence showing that WBC may influence parasympathetic cardiac control and CBT, we hypothesize that WBC helps to improve sleep parameters.

2 | SUBJECTS AND METHODS

2.1 | Subjects

Twenty-two well-trained male athletes or triathletes were recruited for this study. The mean age of the subjects was 23.1 ± 3.5 years. Height, weight, body mass index, and percentage of fat mass were 1.79 ± 5.7 (m), 69.3 ± 8.2 (kg), 23.1 ± 3.5 (kg/m^2), and 11.7 ± 3.6 (%), respectively. Participants had regular sleep schedules, were free of sleep disorders, and were not accustomed to WBC. They did not present any contraindication to cold exposure as recommended by the International Institute of Refrigeration (4). All volunteers provided written consent before beginning the protocol, which complied with the Helsinki declaration and was approved by an ethics committee (IDRCB: 2020-A03563-36). This study included only male participants due to avoid the major changes in sleep patterns, heart rate (HR) variability, and BCT fluctuation that occur during the menstrual cycle (Alzueta & Baker, 2023; Baker et al., 2020; Blake et al., 2023).

2.2 | Experimental design

This study was a randomized controlled crossover protocol. It consisted of three experimental sessions, composed of a training session and one night with sleep analysis. Depending on the experimental condition, subjects were exposed—or not (control session)—to WBC either immediately after training or 1 h before going to bed. All subjects were randomly assigned to each condition (CONT; CRYO 7 p.m.; and CRYO 10 p.m.), spaced 7 days apart.

During the three nights of analysis, sleep was monitored using a specific headband and actimetry and HR variability was recorded. Central temperature and various perceptual measures were also collected during the entire protocol. The experimental design is presented in Figure 1.

2.3 | Training sessions

Participants performed standardized 70-min running training on a track during the three experimental sessions. Each session consisted

of a 25-min warm-up, followed by high-intensity interval training composed of six sets of three min at 95% of the maximal aerobic speed (MAS) with three min of recovery at 60% of MAS. The MAS had previously been obtained by carrying out a VAMEVAL test on a track. This training session took place systematically at 6 p.m. on an outdoor track, with outside temperatures ranging from 5 to 10°C. Participants were accustomed to this type of effort and could adjust their speed using a connected sports watch (Polar V800 GPS, Finland) and were instructed to use the same speed in both trials. A checking was performed a posteriori. All subjects followed the instruction seriously and no speed differences were observed between the two sessions. The perception of effort (RPE) measured at the end of the session was the same after the training sessions (7.4 ± 1.6 , 8.0 ± 1.2 , and 7.6 ± 1.4 for CONT, CRYO 7 p.m., and CRYO 10 p.m. condition, respectively).

After training sessions, participants were subjected to one of the following three conditions: no specific recovery (CONT), WBC exposure after training (CRYO 7 p.m.), or WBC exposure one hour before bedtime (CRYO 10 p.m.). For all conditions, athletes were permitted to take a shower *immediately* after the training sessions, which were consistently performed for less than 5 min and at a temperate temperature. This procedure was the same across all three conditions. Following the training session, participants were instructed to engage in their regular activities until bedtime. However, they were prohibited from using any additional methods of recovery and doing any extra physical activities. They were told to eat a similar meal at the same time in the evening for the three sessions.

2.4 | Whole body cryostimulation (WBC)

WBC exposures took place during two of the three experimental sessions. In the CRYO 7 p.m. condition, WBC exposure was carried out at the end of the training session after drying at approximately 7:00 pm. In the second condition, WBC exposure occurred one hour before going to bed at approximately 10:00 pm. This schedule was individually adjusted so that each participant was exposed one hour before their own bedtime.

Each WBC session consisted of a 30-s exposure in a first chamber at -25°C (perceived temperature of -50°C) and a 3-min

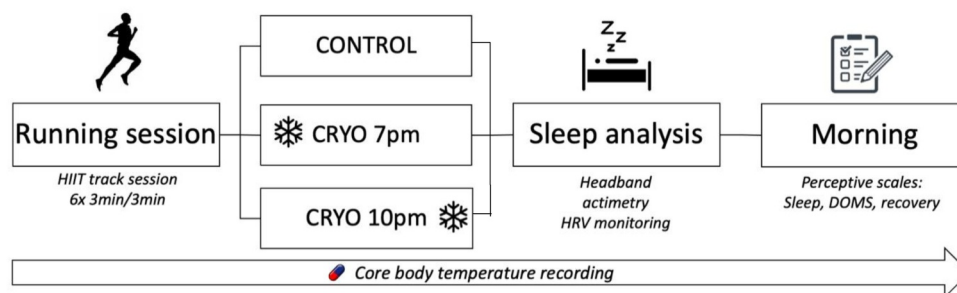


FIGURE 1 Experimental design of the study: randomized controlled crossover protocol with three sessions regarding the recovery condition: control without WBC (CONT); WBC after training at 7 p.m. (CRYO 7 p.m.); WBC before bedtime (CRYO 10 p.m.). The three experimental sessions were seven days apart.

exposure in a second chamber cooled at -70°C (perceived temperature of -110°C) (Aurore Concept, Noisiel, France). Participants entered into the cryo-chamber wearing gloves, slippers, underwear, a cap, and a surgical mask.

2.5 | Measurements

2.5.1 | Perceptual measurements

Participants evaluated their sensations regarding muscle soreness and recovery via perceptive scales for each condition before going to bed and the following morning after sleep. The Likert scale of muscle soreness (Impellizzeri & Maffiuletti, 2007) is graduated from 0 to 6 and the perceived recovery status scale (Laurent et al., 2011) is graduated from 0 to 10.

2.5.2 | Sleep analysis

Sleep was monitored during the three nights of the experimental sessions through objective and subjective measurements. To reduce the sleep disturbance caused by the experiment, the participants slept at home with the equipment we provided. Also, in order to ensure that they were accustomed to the equipment, the participants slept 3 nights as a habituation the week before the beginning of the experiment. During this experiment, bedtime and wake time were not imposed and participants were instructed to keep their usual sleep schedules.

Subjective measurements: Perceived sleep quality was evaluated using the 6-item Spiegel Questionnaire (Spiegel, 1984) and administered the morning following each protocol night. Objective measurements of sleep were studied through analysis of cerebral activity, movements, heart rate variability and body temperature.

Sleep quality and quantity

Sleep quality and quantity of the participants were measured using a wirelessly connected headband (Dreem 2, Paris, France) validated for sleep-related physiological signal recording and sleep stage detection (Arnal et al., 2020). This electronic device is equipped with cerebral activity sensors analyzing several sleep parameters: sleep onset latency, sleep stages (N1, N2, N3, and REM) durations, wake episodes, wake after sleep onset (WASO), and sleep efficiency.

Movements

Actimetry was also used to quantify movements during the night. Subjects were instructed to wear an actigraph (WGT3X-BT monitor, Pensacola, USA) on their nondominant wrist each night of the protocol. Counts on the three-dimensional axis were recorded during the night and various sleep parameters were estimated: sleep efficiency, number and duration of awakenings, and the sleep fragmentation index (Aloulou, Duforez, et al., 2020; Douzi, Dupuy, Tanneau, et al., 2019).

Cardiac autonomic control

Participants wore a Polar H10 HR sensor connected to a Polar watch (Polar V800) to assess cardiac autonomic activity. In this way, RR intervals were recorded during the night before being analyzed with the Kubios HRV software (v. 3.3.1, 2019, Finland) with three types of analyses: one for the signal recorded throughout the entire sleep period, another for the first 4h of sleep, and the third for a 10-min deep sleep period, representative of the first period of SWS. Such procedures have previously been used (Buchheit et al., 2004; Douzi, Dupuy, Tanneau, et al., 2019; Dupuy et al., 2013; Hani et al., 2009). We applied both time and frequency domain methods of HRV analysis. The following parameters were collected: HR, RR intervals, root mean square of standard deviation (RMSSD), parasympathetic nervous system (PNS) index, SD1, SD2, and low frequency (LF)/high frequency (HF) ratios.

Core body temperature

Participants ingested a radiotelemetry pill (BodyCap; e-Celsius® performance) before the training session (5:30 p.m.) to continuously record the core temperature until the following morning. This method is validated and reliable (Bongers et al., 2018) and has been used in many studies investigating temperature variations (Chauvineau et al., 2021; Racinais et al., 2022). The participants' CBT ($^{\circ}\text{C}$) was recorded during the whole night in each experimental session.

2.6 | Statistical analysis

Standard statistical methods were used to calculate the mean and SD. The Gaussian distribution of the data was verified by the Shapiro-Wilk test and homoscedasticity by a modified Levene's test. A two-way analysis of variance (condition \times time) with repeated measures on time was used to test the null hypothesis of an absence of the effect of WBC on our dependent variables. Multiple comparisons were made with the Newman-Keuls post hoc test if an interaction is significant. The significance level was set at $p < 0.05$. All calculations were made with Statistica (Statsoft, Tulsa, USA). The effect size (ES) was calculated with the g of Hedge's formula (Dupuy et al., 2014).

3 | RESULTS

3.1 | Sleep times

The sleep times in the three conditions were the same, with bedtime of $23:48 \pm 01:04$ p.m. for the control condition, $23:34 \pm 00:45$ for the CRYO 7p.m. condition, and $23:38 \pm 00:45$ for the CRYO 10p.m. condition. Wake-up times were $07:28 \pm 01:03$, $07:21 \pm 00:41$, and $07:22 \pm 00:53$ for the control, CRYO 7p.m., and CRYO 10p.m. conditions. CRYO sessions took place at $19:48 \pm 00:11$ p.m. and $22:10 \pm 00:23$ p.m. Durations between WBC exposure and bedtime were $03:46 \pm 00:45$ for CRYO 7 p.m. and $01:30 \pm 00:45$ for CRYO 10 p.m.

3.2 | Perceptual measures

We found no statistical effect of WBC on muscle soreness or perceived recovery. Comparing the results obtained the next morning and those obtained before bedtime, we found a nonsignificant *large* and *moderate* decrease in muscle soreness in the CRYO 7p.m. (from 3.5 ± 1.2 to 2.6 ± 1.3 and ES-0.72) and CRYO 10p.m. (from 3.5 ± 1.0 to 2.8 ± 1.4 and ES-0.57) compared to the control condition (from 3.3 ± 1.5 to 2.9 ± 1.6 and ES-0.24).

Concerning the perception of recovery, we found a nonsignificant improvement the next morning regarding before bedtime, in all conditions, with similar ES amplitudes (CONT: from 3.6 ± 2.2 to 5.6 ± 2.1 , ES 0.9; CRYO 7p.m.: from 4.4 ± 2 to 6.7 ± 1.9 , ES 1.2; and CRYO 10p.m.: from 4.4 ± 1.8 to 6.3 ± 1.8 , ES 1.0).

3.3 | Sleep quality and quantity

Sleep parameters collected through headband and actigraphy are presented in Table 1. We found no difference for any outcome variable between the three nights.

3.4 | Cardiac autonomic control

HR variability parameters are presented in Table 2. Analyses were made for three specific periods during the night: one for the whole night of sleep, the second for the first 4h of sleep, and the third for a representative 10-min deep sleep period (SWS). The ANOVA test revealed a condition effect only in the SWS period and both cryostimulation conditions led to increased parasympathetic control ($p < 0.05$). This effect seems more pronounced for CRYO 10 p.m. as evidenced by a greater modification of RMSSD, SD1, and LF/HF parameters after the experimental night. In the SWS period, the largest effect sizes in most HRV parameters (RMSSD: 0.52; SD1: 0.67; and LF/HF:-0.44) were observed between the CONT and CRYO 10p.m. conditions.

3.5 | Core Body Temperature

CBT was recorded in the three conditions. Pills were ingested before the training session (5:30 p.m.) so that the core temperature was continuously recorded until the following day. We found an effect of time and an interaction between time and condition ($p < 0.05$). Only after bedtime, CRYO 7 p.m. did not induce significant body cooling different from the physiological cooling observable in the CONT condition. However, a significant decrease in CBT in the CRYO 10 p.m. condition was observed ($p < 0.05$). CRYO 10 p.m. induced a drop of greater amplitude than CRYO 7 p.m. was able to generate 2 and 3 h after bedtime. These results are presented in Figure 2A. Furthermore, the temperature was lower during the four hours following WBC exposure when WBC was administrated at 10 p.m. compared with the 7 p.m. session (Figure 2B).

4 | DISCUSSION

This study aimed to explore which exposure schedule for WBC (immediately after training vs. 1h before bedtime) was the most appropriate way to improve sleep and recovery in well-trained athletes. The main results indicated that WBC after training did not modify subjective or objective sleep parameters. However, WBC significantly improved HRV parameters compared to a control condition. More specifically, cardiac parasympathetic activity was more activated during the night when WBC took place 1h before bedtime than in the other experimental conditions. CBT 1h after bedtime was also the lowest in the CRYO 10 p.m. condition, coinciding with a more significant drop in CBT after the WBC session.

In our study, all the measured sleep parameters were similar, independently of the experimental condition, attesting that WBC did not impact sleep architecture or subjective sleep quality in our setting, regardless of exposure timing. Although few studies have focused on the impact of cold strategies on athletes' sleep, several findings have demonstrated the positive effects of this type of recovery. Our research group previously published two studies in which

TABLE 1 Impact of cryostimulation on sleep parameters from cerebral activity recordings.

Sleep parameters	CONT	CRYO 7 p.m.	CRYO 10 p.m.
Total sleep time (min)	427 ± 51	426 ± 49	426 ± 42
Non-REM (%)	77.3 ± 6.1	78.1 ± 4.3	78.2 ± 5.3
REM (%)	22.7 ± 6.1	21.9 ± 4.3	21.8 ± 5.3
SWS duration (min)	115 ± 33	118 ± 22	122 ± 29
WASO (min)	17.2 ± 15.9	18.1 ± 8.9	17.6 ± 7.6
Sleep efficiency (%)	92.1 ± 3.6	92.1 ± 3.2	91.7 ± 2.2
Movements (counts/night)	114 ± 53	110 ± 29	111 ± 32
Perceived sleep quality (0–30)	20.9 ± 3.4	21 ± 3.0	20.6 ± 3.8

Note: Data are presented as mean ± SD.

Abbreviations: REM, rapid eye movement; SWS, slow-wave sleep; WASO, wake after sleep onset.

TABLE 2 Heart rate variability parameters.

HRV parameters		CONT	CRYO 7 p.m.	CRYO 10 p.m.	Significant differences
HR (bpm)	Night	54 ± 6	54 ± 7	52 ± 6	ns
	4h	55 ± 6	55 ± 7	54 ± 7	ns
	SWS	57 ± 7	58 ± 8	54 ± 7	ns
RR (ms)	Night	1132 ± 128	1127 ± 145	1159 ± 142	ns
	4h	1106 ± 130	1103 ± 143	1137 ± 141	ns
	SWS	1068 ± 124	1064 ± 158	1123 ± 145	ns
RMSSD (ms)	Night	71.8 ± 29.2	72.0 ± 30.8	76.3 ± 30.4	ns
	4h	65.4 ± 29.4	67.4 ± 30.2	70.6 ± 29.5	ns
	SWS	45.3 ± 22.4	54.4 ± 26.7	60.5 ± 31.1	(<i>p</i> = 0.05) ^a
PNS index (from -5 to +5)	Night	1.8 ± 1.1	1.8 ± 1.3	2.0 ± 1.2	ns
	4h	1.5 ± 1.1	1.5 ± 1.2	1.8 ± 1.2	ns
	SWS	0.8 ± 0.9	1.0 ± 1.1	1.5 ± 1.1	^a
SD1 (%)	Night	37.0 ± 4.7	37.1 ± 5.4	38.6 ± 4.7	ns
	4h	36.0 ± 5.2	36.9 ± 5.1	38.3 ± 4.7	ns
	SWS	38.4 ± 5.5	40.2 ± 4.7	42.5 ± 5.2	^a
Ratio LF/HF	Night	2.0 ± 1.3	2.1 ± 1.4	1.8 ± 1.2	ns
	4h	2.3 ± 1.7	2.0 ± 1.4	1.8 ± 1.4	ns
	SWS	1.9 ± 1.7	1.4 ± 1.3	1.2 ± 1.1	^{a,b}

Note: Data are presented as mean ± SD.

Abbreviations: HF, high frequency power of the heart rate variability; HR, heart rate; LF, low frequency power of the heart rate variability; PNS, index of parasympathetic nervous system activity; RR, interval beat-to-beat; RMSSD, mean root square of successive differences; SD1, standard deviation 1 of the Poincaré plot nonlinear method, representing parasympathetic activity; SWS, slow-wave sleep.

^aSignificant difference between CONT and CRYO 10 p.m., *p* < 0.05.

^bSignificant difference between CONT and CRYO 7 p.m., *p* < 0.05; and ns = nonsignificant.

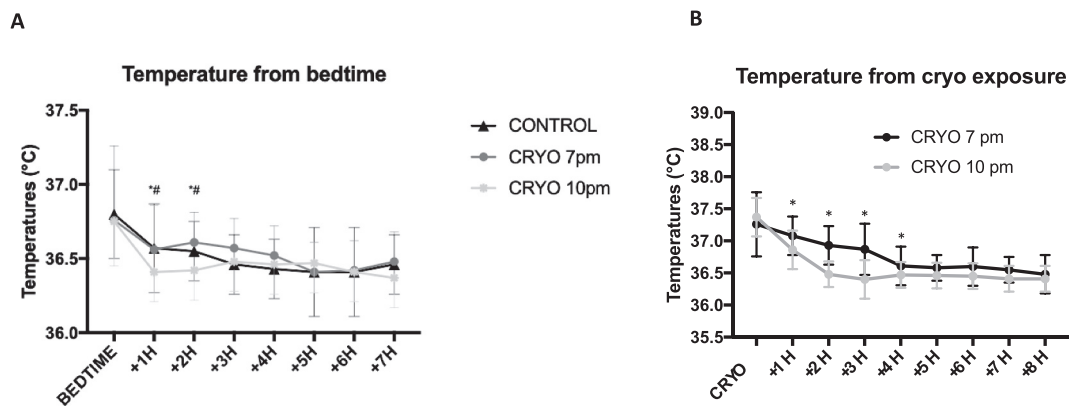


FIGURE 2 (A) The body core temperature following bedtime for all experimental conditions. (*different from control and # different from CRYO 7 p.m. *p* < 0.05). The core body temperature expressed the following WBC exposure. (B) Temperature variations from WBC time of exposure. *Significant difference between CRYO 7 p.m. and CRYO 10 p.m. conditions and *p* < 0.05.

cryostimulation after training reduced the number of movements detected by actimetry during the night (Douzi, Dupuy, Tanneau, et al., 2019; Douzi, Dupuy, Theurot, et al., 2019). The lack of cryostimulation effect on the number of movements compared to previously published studies may be partially explained by the external temperature of the

training session. Indeed, the ambient temperature of the exercise session can have an influence on certain physiological responses. In a recent meta-analysis, Choo et al. (2022) observed that the effect of cold immersion on recovery was greater when the previous physical exercise session was carried out in warm conditions. In the studies by

Douzi et al., the training sessions took place in May–June, whereas our current study took place between November and February, when the outdoor temperature was much colder. The increase in body temperature after exercising is probably more pronounced in hot conditions and the level of fatigue was higher. Therefore, we could hypothesize that cryostimulation may have more impact when the training session is performed in hot rather than cold conditions. These aspects should be studied in the future.

Another cooling strategy commonly used by athletes is CWI. With this technique, (Haddad et al., 2012) showed in elite swimmers that 5min-CWI at 15°C after evening training was likely to be associated with greater sleep quality than passive recovery. Similarly, the recent results of Chauvineau et al. (2021) evidenced the beneficial effects of CWI, especially when the head was included in the cold immersion. Reduced arousals and limb movements at night were observed for the participants who underwent the 10-min whole body CWI at 13.3°C after a simulated trail session. The subjects also exhibited a higher SWS proportion during the first part of the night, indicating that the cooling strategy before sleep may modulate its structure. However, in our protocol, we did not observe any changes during the analyzed nights in the different sleep stages. This may be due to limitations relative to the context of our experiments and the population under consideration. Indeed, our participants were good sleepers without sleep disturbances, and the experiments were conducted throughout the winter season. Such contexts may not be the most favorable for observing the potential effects of WBC on sleep. In any event, these results are in accordance with Aloulou, Leduc, et al. (2020) who failed to see a positive impact of cryostimulation on sleep architecture after a professional rugby match.

Nevertheless, it appears interesting to use cooling strategies to promote post-training parasympathetic tone activation. Several studies previously reported that resting vagal-related HRV indices increased after cryostimulation exposure. Indeed, the WBC session after intense training induced a strong parasympathetic reactivation in elite athletes from the exposure (Hauswirth et al., 2011, 2013). Similarly, CWI after training induced beneficial effects on the parasympathetic cardiac system (Haddad et al., 2012). Our study compared the effects of two different exposure timings to WBC on cardiac autonomic control after evening training, as assessed by night HRV, which has not been previously done. The main results were observed during the SWS stage. This stage of sleep architecture is particularly important for physical recovery since it is when protein synthesis and tissue remodeling stimulation occur. During this stage in our study, several variables (RMSSD, PNS index, SD1, and LF/HF ratio) reflecting cardiac parasympathetic control were upregulated in CRYO 10 p.m. versus the CONT condition. RMSSD score, the most reproducible variable, was higher when WBC exposure occurred 1h before bedtime. The other indices supported this result as we observed a trend toward a difference in the 4h and whole night analyses. Previous investigations of our team reported similar results to those of the present study with WBC conducted immediately after the evening training. When analyzing the whole night and the first 4h periods, HRV parameters were unaffected by WBC. In contrast, SWS analysis was characterized by a parasympathetic activation in the

WBC group compared to passive recovery. This was attested by a lower LF/HF ratio, indicating greater parasympathetic activity during the SWS episode following WBC (Douzi, Dupuy, Tanneau, et al., 2019). Overall, the predominance of cardiac parasympathetic drive after cold exposure is well-validated and is part of the mechanisms accelerating post-exercise recovery. Our results confirmed this phenomenon and indicated the interest of adjusting WBC exposure timing, with further benefits when WBC is scheduled very close to bedtime. We can suppose that the cardiac parasympathetic control upregulation observed during deep sleep contributed to the implementation of recovery functions and improved sleep quality.

One of the significant interests of cold exposure after intense training is to enhance sleep quality through the modulation of CBT. Indeed, several studies have demonstrated that cooling strategies after evening training yield a reduction of CBT, which may be one of the mechanisms involved in the improved sleep quality (Herberger et al., 2024) and observed by Chauvineau et al. (2021) in their study using post-training CWI. Previously, Robey et al. (2013) reported decreased CBT after CWI, with decreased temperatures observed until the first 3h of subsequent sleep. Nonetheless, whole night sleep architecture and perceived sleep quality were not affected by this cooling strategy. We observed similar results in our present study, with no effect of WBC on sleep structure but a significant drop of CBT after WBC, regardless of exposure timing. However, cryostimulation occurring before bedtime (CRYO 10 p.m.) induced more benefits regarding BCT modulation than its implementation immediately after training (CRYO 7 p.m.). It triggered an earlier drop in BCT and led to lower CBT one hour after bedtime. Potentially, the combination of cold exposure and circadian rhythm contributed to this CBT decrease and may have been responsible for the parasympathetic tone activation observed during the first hours of sleep.

Regarding perceptual recovery measures, while the differences between conditions did not reach statistical significance, the effect sizes observed are in accordance with previous studies using cryostimulation as a recovery technique. Including data from 72 subjects, a meta-analysis by (Dupuy et al., 2018) highlighted decreased muscle soreness due to WBC exposure. In a group of resistance-trained males, it was demonstrated that WBC attenuated muscle soreness 24h post-training. It was associated with a decrease in C- Reactive Protein (CRP), a marker of inflammation (Wilson et al., 2019). After damaging exercise, Fonda & Sarabon, (2013) reported reduced muscle soreness after WBC. Similarly, Hauswirth et al. (2011) reported that WBC after a damaging running session was beneficial for perceived pain and subjective fatigue compared to passive recovery. Other studies on the effects of cooling strategies in professional tennis players reported improved functional recovery after WBC (Poignard et al., 2020; Ziemann et al., 2012). Our present study is quite in line with the positive effect of WBC on muscle soreness and perceived recovery after training (based on ES data). Indeed, whatever the time of WBC exposure (7 p.m. or 10 p.m.), muscle soreness tends to be reduced (also based on the ES) the morning after, whereas no reduction was observed in the CONT condition.

Although the results of this study are very promising, they should be interpreted with caution as further research is needed

concerning intersex comparisons before they can be generalized. Indeed, the responses in women to cryostimulation may differ from those in men (Solianik et al., 2014; Theurot et al., 2021, 2023) and the influence of the menstrual cycle may also be important to investigate.

CONCLUSION

The objectives of this study were (i) to evaluate the effect of WBC after training as an effective tool to improve sleep and recovery and (ii) to determine which exposure schedule for WBC (immediately after training vs. 1h before bedtime) is the most appropriate to improve sleep and recovery. In this experimental context, WBC seems to improve sleep through improvements of cardiac parasympathetic control during SWS. This technique enhances the SWS stage through cardiac parasympathetic modulation and exposure near bedtime provides better benefits. A larger drop in the CBT with this timing exposure may partially explain this observation. Our findings would be helpful for coaches and staff decisions regarding the timing of WBC as a recovery strategy.

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CONFLICT OF INTEREST STATEMENT

The authors declare that they have no conflicts of interest.

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APPENDIX

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