Whole-Body Cryostimulation Limits Overreaching in Elite Synchronized Swimmers

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ABSTRACT

SCHAAL, K., Y. LE MEUR, J. LOUIS, J.-R. FILLIARD, P. HELLARD, G. CASAZZA, and C. HAUSSWIRTH. Whole-Body Cryostimulation Limits Overreaching in Elite Synchronized Swimmers. *Med. Sci. Sports Exerc.*, Vol. 47, No. 7, pp. 1416–1425, 2015. **Introduction**: Elite athletes frequently undergo periods of intensified training (IT) within their normal training program. These periods can lead athletes into functional overreaching, characterized by high perceived fatigue, impaired sleep, and performance. Because whole-body cryostimulation (WBC) has been proven to be an effective recovery method in the short term (<76 h), we investigated whether daily WBC sessions during IT could prevent exercise and sleep-related signs of overreaching. **Methods**: After a normal training week (BASE), 10 elite synchronized swimmers performed two 2-wk IT periods in a randomized crossover fashion using WBC daily (IT_{WBC}) or not (IT_{CON}), separated by 9 d of light training. Swim time trials (400 m) were performed at BASE and after each IT to quantify blood lactate ($[La^-]_B$), HR (HR_{400}), salivary alpha amylase ($[\alpha\text{-amylase}]_{s400}$), and cortisol ($[cortisol]_{s400}$) responses. Swimmers wore a wrist actigraph nightly to monitor sleep patterns. **Results**: Swim speed (400 m), $[La^-]_{B400}$, and $[\alpha\text{-amylase}]_{s400}$ decreased from BASE to IT_{CON}, although no significant changes were found after IT_{WBC}. Decreased swim speed was correlated to decreased HR_{400} and $[cortisol]_{s400}$. During IT_{CON}, significant decreases in actual sleep duration (−21 ± 7 min) and sleep efficiency (−1.9% ± 0.8%) were observed, with increased sleep latency (+11 ± 5 min) and fatigue compared with BASE, although these variables did not change during IT_{WBC}. Using a qualitative statistical analysis, we observed that daily WBC use resulted in a 98%, 59%, 66%, and 78% chance of preserving these respective variables compared with IT_{CON}. **Conclusion**: WBC use during IT helped mitigate the signs of functional overreaching observed during IT_{CON}, such as reduced sleep quantity, increased fatigue, and impaired exercise capacity. These results support the daily use of WBC by athletes seeking to avoid functional overreaching during key periods of competition preparation. **Key Words:** RECOVERY, OVERREACHING, ELITE ATHLETE, SLEEP QUALITY, PERFORMANCE

APPLIED SCIENCES

Elite athletes in many sports follow rigorous, carefully planned training regimen designed to optimize peak performance during the most important competitions of the season. Periods of intensified training (IT) are inherent to these athletes' training programs and are intended to impose a large enough training stress to further stimulate the physiological adaptations that are necessary to improve performance. As such, periods of IT deliberately induce an imbalance between training stress and recovery, which may lead the athlete into a state of functional overreaching, and a state of fatigue accumulation associated with reduced performance, immune function, and mood disturbances (34). Functional overreaching is detrimental to performance in the short term. However, when appropriate periods of recovery are provided, a "supercompensation" effect may occur, in which the physiological responses are able to compensate for the training-related stress, and the athlete can exhibit enhanced performance (34). Although IT periods may provide the stimulus needed to trigger the desired physiological adaptations, Aubry et al. (3) have recently shown that developing functional overreaching during IT may actually diminish the gain in performance that can be obtained after the recovery period compared with completing IT while avoiding overreaching altogether. Therefore, finding means by which to recognize the early signs of functional overreaching may help to optimize the effective training of elite athletes.

As outlined in a recent consensus statement, functional overreaching (F-OR) can be recognized by a combination of physiological and psychological changes, including increased perceived fatigue, adverse mood changes, a persistent decrease in performance, and a suppressed physiological response to submaximal and maximal exercise (28,29,34). Le Meur et al. (28) demonstrated that the state of F-OR may be recognized by

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the altered cardiovascular, metabolic, and subjective responses to absolute submaximal exercise intensities. They reported that reduced blood lactate accumulation, reduced HR, and increased RPE at fixed submaximal workloads could accurately discriminate athletes who developed F-OR after IT from control athletes who continued their normal training. The increased sympathetic and adrenal activity in response to the intensified exercise and training stress, together with insufficient recovery, may be responsible for some of the physiological changes observed in F-OR athletes (26). Over time, persistent sympathoadrenal activation may result in central and/or peripheral adaptations resulting in a suppressed physiological response to acute stressors, such as intense exercise. A blunted sympathetic response to exercise has been reported in functionally overreached athletes (29,42,43).

The increased sympathoadrenal activation during IT periods could also affect the quality of passive recovery by impairing sleep (8,36). Adequate sleep constitutes one of the most important aspects of recovery from the demands of heavy training, and decreased sleep quality has been shown to occur with increased training stress (9,16,41). Few longitudinal free-living studies have described sleep patterns during IT periods, and most of these have been limited to using subjective measures of sleep quality (19,23) despite the poor agreement that has been found between subjective and objective ratings of sleep quality (33). Recently, Hausswirth et al. (16) used wrist actigraphy to monitor well-trained triathletes and reported significantly impaired sleep quality in subjects who developed F-OR as a result of 3 wk of IT, whereas those who avoided F-OR despite following the same IT protocol did not show these adverse sleep pattern changes.

Finding means by which to preserve athletes' sleep quality during highly demanding training periods may therefore enhance their ability to recover and avoid F-OR (16). Acute cold exposure, in the form of cold-water immersion or dry-air whole-body cryostimulation (WBC), is a recovery strategy increasingly used by high-level athletes. Cold exposure induces a number of physiological effects thought to be beneficial for athletic recovery, including enhanced parasympathetic reactivation at the cardiac level after exercise (1,2,39) and reduced inflammation response (37). Cold exposure has been shown to increase pituitary (13) and plasma (12,13,44) beta-endorphin concentrations, producing an analgesic effect and a sensation of well-being (22). Yet, to our knowledge, only two studies have investigated the effect of cryostimulation on *subjective* ratings of sleep quality in athletes and reported a positive influence of cryostimulation on these ratings (20,21). However, studies have demonstrated a poor correlation between subjective and objective parameters of sleep quantity and quality in athletes as well as the general population (16,33), and no study has yet investigated whether daily WBC use by elite athletes could preserve objective sleep parameters during increased training stress. The aims of the present study were therefore 1) to describe changes in sleep quality and physiological markers of stress and fatigue in elite athletes undergoing typical IT periods and 2) to test the hypothesis that daily WBC sessions during IT could maintain sleep quality and limit the severity of physiological and psychological markers of fatigue that have been previously reported in functionally overreached athletes.

METHODS

Study Population

This study was performed on female synchronized swimmers competing at the international level. These athletes adhere to high-volume, high-intensity training regimens, often training twice per day on most days of the week (31). Over the months preceding major competitions, it is typical for them to undergo IT periods, during which the physical training load is increased primarily via an increase in the intensity of exercises performed. As the amount of passive recovery time available between training bouts is short for athletes training more than once per day, it is important to optimize the quality of the synchronized swimmers' recovery time during IT periods to avoid functional overreaching. Eleven elite synchronized swimmers were enrolled in the study, and 10 completed the protocol. One swimmer sustained an injury during the protocol, and her data were excluded from the analyses. Swimmers were 20.4 ± 0.4 yr of age and had been training as part of the senior French national team for 2.5 ± 0.4 yr. Swimmers were in residence at the training center where this protocol took place (INSEP: National Institute of Sport, Expertise and Performance) and were well-trained at the beginning of the study ($\dot{V}O_{2max}$ = 62.1 ± 0.3 $mL \cdot kg^{-1} \cdot min^{-1}$). All swimmers underwent a medical clearance examination to rule out any potential contraindications to WBC (such as cardiovascular diseases, acute kidney and respiratory tract diseases, Raynaud's syndrome, cold allergy, etc.)

Study Design

The protocol was scheduled in the early competition period, starting 11 wk before the qualification tournament for the 2012 London Olympic Games. After 1 wk of normal training (BASE), the swimmers performed two 2-wk IT periods in randomized order (Fig. 1): one control IT period (IT_{CON}), during which no specific recovery strategy was allowed (i.e. no massages, hydrotherapy, sauna/steam baths), and one that included daily WBC sessions (IT_{WBC}). Each IT period was programmed similarly by the coaches, aiming to increase the overall load to 125% of BASE, as described below. The two periods of IT were separated by a 9-d taper period consisting of light training. Because all 10 swimmers in this study were regularly taking exogenous hormonal contraceptives, we did not need to take fluctuations of ovarian hormones into consideration for this protocol. The study conformed to the ethical guidelines set forth in the Declaration of Helsinki and was approved by the Ethical Committee of Saint-Germain-en-Laye (acceptance no. 12048). The swimmers were informed about the study protocol, the risks of all tests, and their rights

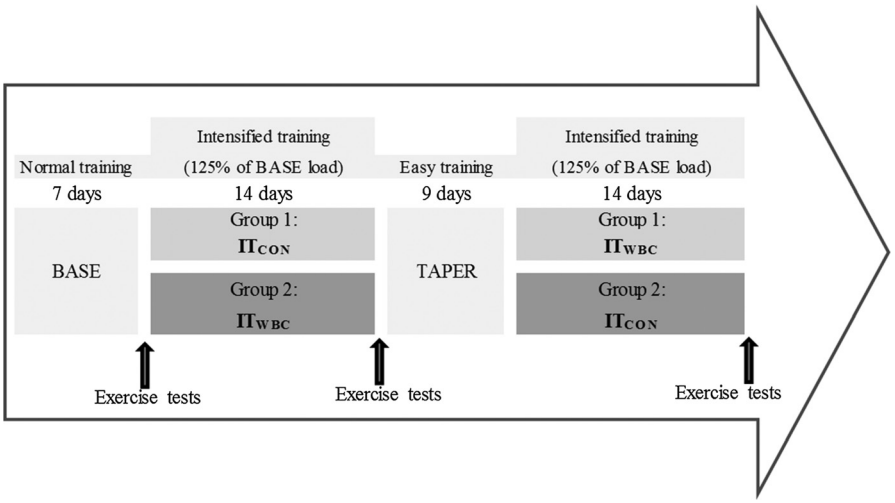

FIGURE 1—Experimental design. IT_{CON}, control period of IT; IT_{WBC}, IT with daily sessions of WBC.

and provided their written informed consent to participate before the protocol was initiated.

Assessment of the Training Load

The contrast in training load between BASE and each IT was measured using the method introduced by Foster et al. (10,11). Although the original method used a 10-point modified Borg scale of perceived exertion to describe the intensity of each training session, we used the original 6–20 Borg scale (4) that the swimmers were well accustomed to. Because of the wide variety of exercise types that may be performed in a single day, swimmers were asked to provide an RPE for each hour of exercise performed that day. The weekly training load was then measured as the product of training duration (min) × RPE per session, in arbitrary units (AU) (14).

Exercise Testing Sessions

At the beginning of the experimental period, a preliminary 400-m freestyle swimming time trial ($TT_{400\text{-PRE}}$) was performed to establish a current performance level of the swimmers and to establish each swimmer's submaximal swim speeds as described below. The TT_{400} is a typical test performed by swimmers to assess cardiorespiratory fitness (24), and these synchronized swimmers were well accustomed to it. Three exercise test sessions were subsequently performed: during BASE, at the end of IT_{CON}, and at the end of IT_{WBC}. The sessions were scheduled on the same day and time each week after two consecutive days of recovery (no exercise training) to ensure that performance variations during the maximal incremental tests were due to the global training regimen and not due to fatigue accrued over the training session(s) performed over preceding days (28). The swimmers were asked to consume their typical precompetition meals during the day preceding the test session, and they were instructed to eat until reaching satiety to replenish glycogen stores. During the testing sessions, the swimmers were only allowed to consume water.

Graded exercise test. After a standardized 15-min warm-up, the swimmers performed a submaximal swimming test consisting of three 200-m swim intervals performed at predetermined speeds. These three speeds were kept constant throughout the protocol for each swimmer to compare potential changes in the physiological and psychological response to the same absolute workloads throughout the study. This submaximal exercise protocol was modeled after the test described by Le Meur et al. (28) who showed that decreased HR and blood lactate concentrations ($[La^-]_b$) during absolute submaximal exercise intensities could predict a state of functional overreaching in well-trained triathletes. Speed 1 (s1) was set to 70% of $TT_{400\text{-PRE}}$ speed, perceived as "very light" (9) during BASE on the RPE scale (4); speed 2 (s2) corresponded to 80% of $TT_{400\text{-PRE}}$ speed, perceived as "light" (11); and speed 3 (s3) corresponded to 90% of $TT_{400\text{-PRE}}$ speed, perceived as "somewhat hard" (13). Swimmers were instructed to keep pace with one individual walking along the length of the pool at the adequate speed for each interval. At the end of each interval, swimmers stopped swimming for 60 s to provide their RPE, and a blood sample was obtained from the earlobe to measure $[La^-]_b$ using a portable analyzer (Lactate Pro™; Arkray Inc., Kyoto, Japan). HR was recorded continuously throughout the exercise test session by an HR monitor (Polar RS400, Kempele, Finland), and the values obtained over the last 30 s of each swimming speed were averaged and used as the mean HR for that stage.

Maximal exercise test. After a 5-min rest interval after the completion of the third submaximal stage (remaining in the pool), swimmers performed an individual 400-m freestyle time trial (TT_{400}). They received no feedback on their pace during the trial, and HR was monitored continuously. Immediately upon completing the trial, swimmers indicated their RPE and an ear stick was performed to measure $[La^-]_b$. Within the first minute after the completion of the TT_{400}, the

swimmers also provided a saliva sample via passive drool to measure salivary α-amylase ([α-amylase]$_{s400}$) and cortisol ([cortisol]$_{s400}$) as endocrine markers of noradrenergic and hypothalamic–pituitary–adrenal activity (6,35), respectively.

WBC Sessions

Every day during IT_{WBC}, at the end of the last training session (between 18:00 and 19:00), the swimmers went directly to the training center's medical department, where they underwent a WBC session under medical supervision. After fully drying their hair, putting on a dry bathing suit, gloves, socks, an ear band, face mask, and rubber clogs, the swimmers passed through three consecutive rooms (Zimmer Elektromedizin, Germany) whose temperature was continuously controlled (−10°C, −60°C, and −110°C). Once the room reached −110°C, they were asked to walk slowly around the room while also moving their arms for 3 min. At the end of the session, the swimmers changed into their regular clothes and laid down for 15 min in lounge chairs in an adjacent room to relax while warming back up.

Sleep Analysis

Every night throughout the study, swimmers wore a wrist actigraph (Actiwatch; CamNTech Inc., England) to monitor sleep patterns. They were asked to press the time stamp button on the actigraph upon switching the lights off (considered as the bed time) and to press it again upon waking up (sleep end) and to take it off upon getting up. The sleep variables used for analysis were as follows:

- Total time in bed (bed time to get-up time)
- Bed time, sleep start, sleep latency (sleep start − bed time), and get-up time,
- Actual sleep time (assumed sleep time − wake time as determined by the algorithm)
- Sleep efficiency: actual sleep time/total time in bed.

No specific bedtime schedule was imposed to the swimmers during the study to observe how changes in training intensity may affect self-selected bedtimes and get-up times. The morning and afternoon training schedules remained the same throughout the study. Values obtained nightly within each training period were then averaged for subsequent statistical analysis.

Psychological Variables

Every morning throughout the study protocol, the swimmers were asked to rate the following items in a daily log: perceived fatigue and perceived sleep quality, on a scale from 1 to 7 (19) (1 being the most positive rating—very, very low fatigue and very, very good sleep quality; 4 being "normal"; and 7 being the most negative—very, very high fatigue and very, very bad sleep quality). These daily variables were also averaged within each period for further analysis.

Endocrine Analyses

On the morning of the exercise tests and at the end of each period, the swimmers provided a 4-mL saliva sample via passive drool. The samples were obtained at 7:00 and were kept refrigerated until brought to the investigator at 8:00. The samples were then promptly frozen at −80°C. At the end of the intervention period, samples were thawed and centrifuged at 3000*g* for 10 min, and standard enzyme-linked immunoassay procedures were used to determine salivary cortisol ([cortisol]$_s$, IBL International; Toronto, ON, Canada) and alpha amylase concentrations ([α-amylase]$_s$, IBL International) in duplicate measurement. The assay for [α-amylase]$_s$ had an intraassay coefficient of variation (CV) of 3.7% to 2.3% over an activity range of 47.0–166 $U \cdot mL^{-1}$ and an interassay CV of 6.2% to 6.9% over an activity range of 34.7 to 260 $U \cdot mL^{-1}$. The assay for [cortisol]$_s$ had an intraassay CV of 7.3% to 3.1% over a concentration range of 0.27–2.34 $\mu g \cdot dL^{-1}$ and an interassay CV of 8.8% to 6.4% over 0.54–2.35 $\mu g \cdot dL^{-1}$.

Statistical Analysis

All data were kept in an electronic database and analyzed using specialized statistical software (Statistica 7.0). The normality of distribution for each variable was tested using the Shapiro–Wilk test. Changes in each variable from BASE to IT_{CON} and IT_{WBC} were evaluated using repeated-measures ANOVA, introducing the order in which the two IT protocols were performed as a blocking variable. When the ANOVA reached our accepted significance threshold ($\alpha = 0.05$), Tukey's honest significant difference test was then performed as post hoc analysis to further discern differences between BASE, IT_{WBC}, and IT_{CON}. When assumptions of normality or homogeneity of variances were not met, the data were log transformed before analysis. Means were then detransformed back to their original units.

Changes in performance and in sleep variables were further analyzed using the magnitude-based inference approach recommended for exercise science studies (21). We used this qualitative approach to complement the traditional statistical analyses described above, to convey the magnitude of an effect, which is typically more relevant to performance than any statistically significant effect. Performance and sleep data were log transformed before analysis to reduce bias arising from nonuniformity of error for performance changes analysis. The magnitude of the between-condition changes were expressed as standardized mean differences (Cohen's *d*), which were calculated using the pooled SD (7) in modified statistical spreadsheets (20). The magnitude of the percentage change in sleep variables or in 400-m TT speed was interpreted by using values of 0.3, 0.9, 1.6, 2.5, and 4.0 of the within-athlete variation (CV) as thresholds for *small*,

moderate, *large*, *very large*, and *extremely large* differences between the trials (9). For performance, this threshold was calculated using the CV (%) of performance during the two 400-m time trials performed during baseline. For sleep variables, thresholds were calculated using the CV of each variable measured over 2 wk of normal training. CV (0.3) was thought to represent the smallest worthwhile change as proposed by Hopkins et al. (20). Finally, Pearson correlations were performed to examine possible associations between changes in stress hormones, sleep quality, and subjective variables of fatigue such as changes in mood and perceived difficulty of exercise. Correlations were performed on the BASE-IT differences, combining the two IT conditions ($n = 20$). When a correlation was statistically significant, the following criteria were used to interpret the size of the correlation between the two variables: <0.1, trivial; 0.1–0.3, small; 0.3–0.5, moderate; 0.5–0.7, large, 0.7–0.9, very large, and 0.9–1.0, almost perfect (21).

RESULTS

Exercise Training Load

The number of training hours remained the same during BASE, IT_{WBC}, and IT_{CON} (25.4 ± 0.6, 25.4 ± 0.5, and 24.3 ± 0.4 h·wk^{-1}, respectively), but the overall training load for each period, expressed as the product of RPE × minutes, increased from 17,940 ± 1740 to 22,920 ± 2100 AU (+25%, $P < 0.001$ vs. BASE) and 22,380 ± 1320 AU (+28%, $P < 0.001$ vs. BASE) for each period, respectively. There was no difference in training load between IT_{WBC} and IT_{CON}.

Physiological Response to Exercise

Submaximal exercise. Table 1 presents the physiological response to submaximal exercise at the end of each period. Both IT periods resulted in a significant decrease in $[La^-]_b$ and HR; however, RPE was lower during s1, s2, and s3 after IT_{WBC} compared with BASE. Changes in RPE at all submaximal intensities were directly correlated to the change in perceived fatigue upon waking (Table 2).

TABLE 1. Mean ± SE values for submaximal and maximal exercise variables during three 200-m intervals at three different fixed swim speeds (s1, s2, and s3) and a 400-m time trial (TT_{400}).

	Intensity	BASE	IT_{WBC}	IT_{CON}
HR (bpm)	s1	126 ± 4	120 ± 3*	120 ± 2*
	s2	136 ± 3	132 ± 4	131 ± 2
	s3	156 ± 3	147 ± 4*	151 ± 3
	TT_{400}	183 ± 3	180 ± 4	179 ± 3
$[La^-]_B$ (mmol·L^{-1})	s1	1.9 ± 0.2	1.4 ± (0.1)*	1.4 ± 0.2*
	s2	1.9 ± 0.2	1.5 ± (0.1)*	1.4 ± 0.1*
	s3	2.5 ± 0.2	2.0 ± (0.2)*	1.9 ± 0.2**
	TT_{400}	7.6 ± 0.2	7.3 ± (0.2)	6.8 ± 0.2*
RPE (6–20 scale)	s1	9 ± 1	8 ± 0.5	9 ± 1
	s2	11 ± 1	10 ± 1	11 ± 1
	s3	12.5 ± 1	12 ± 1	13 ± 1****
	TT_{400}	17 ± 1	17 ± 1	17 ± 1

*$P < 0.05$, different from BASE.
**$P < 0.01$, different from BASE.
***$P < 0.005$, different from BASE.
****$P < 0.05$, different from IT_{WBC}.

TABLE 2. Correlations between changes in variables of stress (α amylase), sleep, fatigue, and performance.

Variable	Correlated With	*R*	*P* (Two-Tailed)
$\Delta[\alpha\ amylase]_s$	RPE at s3	0.56	0.010
	ΔSleep latency	0.44	0.052
	ΔPerceived fatigue	0.44	0.052
	ΔSleep efficiency	−0.54	0.014
ΔPerceived fatigue	$\Delta[\alpha\ amylase]_s$	0.44	0.052
	ΔRPE s1	0.59	0.006
	ΔRPE s2	0.62	0.003
	ΔRPE s3	0.70	<0.001
ΔTT_{400} speed	$\Delta[Cortisol]_{s400}$	0.78	<0.001
	ΔHR_{400}	0.67	<0.001

The symbol Δ refers to the change in the given variable from BASE to IT.

Maximal exercise. A significant decrease in mean TT_{400} speed was observed from BASE to IT_{CON} (−1.1% ± 0.9%, $P = 0.049$, *trivial* to *moderate* effect, Fig. 2). After IT_{WBC}, however, mean swim speed did not change significantly (−0.5% ± 0.9%, $P = 0.313$, *unclear* effect). The difference in swim speed between IT_{WBC} and IT_{CON} was *unclear* (+0.7% ± 0.9%). The decrease in performance during IT_{CON} was accompanied by significant reductions in $[La^-]_{B400}$ ($P = 0.002$) and $[\alpha\text{-amylase}]_{s400}$ ($P = 0.031$). After both IT, changes in 400-m speed from BASE showed *large* and *very large* correlations to changes in HR_{400} ($R = 0.67$, $P = 0.001$) and $[cortisol]_{s400}$ ($R = 0.78$, $P < 0.001$). RPE_{400} did not change significantly but showed a *moderate* inverse correlation to $[cortisol]_{s400}$ ($R = -0.43$, $P = 0.05$, Table 2).

Sleep Analysis

Sleep variables obtained from the Actiwatch and sleep questionnaires are presented in Table 3. Both IT periods showed a significant change in the mean bed time and get-up time of the swimmers despite their training schedules remaining the same each week throughout the study. Swimmers retired to bed 40 ± 11 ($P = 0.001$) and 49 ± 10 min later ($P < 0.001$) during IT_{WBC} and IT_{CON} compared with BASE and got up in the morning 52 ± 8 ($P < 0.001$) and 38 ± 7 min later ($P < 0.001$), respectively. Although it was *unclear* whether bed time occurred earlier during IT_{WBC} than IT_{CON} (−9.1 ± 18.2 min), IT_{WBC} was associated with a *trivial to very large* positive effect on the get-up time (13.2 ± 17.2 min). As a result, IT_{WBC} had a *small to large* positive effect on the total amount of time in bed compared with IT_{CON} (+4.9% ± 3.1%).

During IT_{CON}, sleep latency increased ($P = 0.053$) because the swimmers took an additional 11 ± 5 min to fall asleep (45.0% ± 35.9%, *trivial to very large* effect). No significant difference in sleep latency was reported when comparing IT_{WBC} with BASE (+25.4% ± 56.9%, $P = 0.331$, *unclear* effect) and IT_{CON} (−13% ± 35.2%, $P = 0.311$, *unclear* effect). The actual sleep duration was significantly decreased during IT_{CON} compared with BASE ($P = 0.047$), with swimmers losing 21 ± 7 min of sleep per night (−4.7% ± 3.1%,

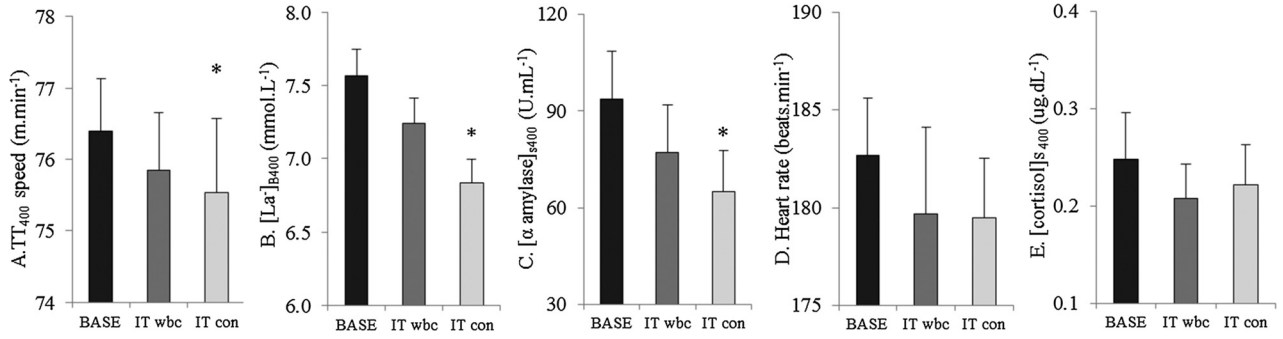

FIGURE 2—Maximal exercise performance and physiological response to 400-m swimming time trial. A, TT_{400} speed ($m \cdot min^{-1}$). B, $[La^-]_{B400}$ ($mmol \cdot L^{-1}$). C, $[\alpha\text{-amylase}_s]_{400}$ ($U \cdot mL^{-1}$). D, HR (bpm). *Significantly different from BASE, $P < 0.05$.

small to large effect), whereas no changes were observed during IT_{WBC} (0.6% ± 5.1%). Compared with IT_{CON}, IT_{WBC} had a significant ($P = 0.046$) positive effect on actual sleep duration (5.5% ± 3.1%, *small to large* effect). xIT_{CON} showed a significant decrease in sleep efficiency from BASE (−2.3% ± 1.8%, $P = 0.05$, *moderate* to *very large* effect), whereas IT_{WBC} showed no significant difference from BASE and IT_{CON} (0.5% ± 1.9%, $P = 0.9$, *unclear* effect). Although sleep questionnaire ratings revealed a significant increase in perceived fatigue during IT_{CON} ($P = 0.049$, *trivial* to *large* effect), there was no significant difference during IT_{WBC} compared with BASE ($P = 0.69$, *unclear* effect). We did not observe a significant difference in perceived fatigue between IT_{WBC} and IT_{CON}, but there was a 78% chance for fatigue levels to be lower after IT_{WBC} (−6.5% ± 8.7%, *trivial to large* effect). Ratings of perceived sleep quality did not change. Changes in perceived fatigue from BASE to both IT also showed *large* correlations with changes in RPE at s1, s2, and s3 (Table 2).

Resting Endocrine Parameters

Fasted waking $[cortisol]_s$ did not change significantly from BASE to either IT period (Fig. 3). There was no significant difference in waking $[\alpha\text{-amylase}]_s$ between any of the conditions. However, the change in resting $[\alpha\text{-amylase}]_s$ was negatively correlated with change in sleep efficiency ($P = 0.014$, *moderate* correlation) and trended toward a positive correlation with the change in sleep latency and perceived fatigue ($P = 0.052$ for both *small* correlations) during both IT conditions (Table 2).

DISCUSSION

This study is the first, to our knowledge, to evaluate the effect of typical IT periods on physiological and psychological indicators of recovery, fatigue, and performance in elite synchronized swimmers. We showed that the periods of intense training performed over the months preceding the swimmers' major competitions led to the appearance of early signs of the overreached state, including an impaired autonomic and metabolic response to exercise, increased perceived fatigue, and deteriorations in sleep quantity and quality, which were all observed during IT_{CON}. This study is also the first to use a longitudinal design to investigate the effectiveness of WBC as a daily recovery strategy during IT. The present results suggest that several of the physiological signs of functional overreaching observed during IT_{CON} could be reduced by daily sessions of WBC. The latter improved the quality of the swimmers' recovery by preserving sleep quantity, preventing increases in levels of perceived fatigue, and maintaining performance and the physiological response to maximal exercise.

Effects of training overload on the physiological response to exercise and sleep. Upon completion of IT_{CON}, physiological changes observed during fixed-intensity submaximal exercise pointed to an early state of functional overreaching. The highest submaximal exercise intensity, s3, was associated with a suppressed HR response and $[La^-]_B$ accumulation concomitantly with increased RPE. These results agree with recent findings by Le Meur et al. (28) who described that decreased HR and $[La^-]_B$ with increased RPE at fixed submaximal intensities could accurately discriminate functionally overreached high-level triathletes from nonoverreached controls. Previous studies have reported blunted sympathetic (27,29,43) and pituitary–adrenal (42) responses to exercise after periods of IT . At the end of the control IT period, the reduction in $[\alpha\text{-amylase}]_{s400}$ and $[La^-]_{B400}$ and the correlations between decreased TT_{400} speed and suppressed HR and $[cortisol]_{s400}$ suggest a reduced sympathetic and adrenal response to exercise in fatigued athletes. The decrease in $[\alpha\text{-amylase}]_{s400}$ observed after IT_{CON} may reflect a reduced synaptic norepinephrine secretion and spillover into the circulation (6,35), and the reduced blood lactate accumulation observed at the end of s3 and TT_{400} also suggests a reduced rate of energy production from glycolysis, possibly due to the suppressed adrenergic response to exercise.

Poor sleep during periods of IT has been associated with functional overreaching in athletes, although it remains unclear whether decreased sleep quality is a cause or a symptom of overreaching (34). To our knowledge, only two studies have examined longitudinal changes in sleep patterns during IT in athletes using wrist actigraphy under free-living conditions

TABLE 3. Sleep actigraphy and sleep questionnaire variables.

	BASE	IT_{WBC}	IT_{CON}	SWC		$BASE–IT_{WBC}$	$BASE–IT_{CON}$	$IT_{WBC}–IT_{CON}$
Bed time (h:min)					Difference[a]	40. 2 (19.8; 60.6)	49.3 (31.8; 66.8)	−9.1 (−27.3; 9.0)
	22:52 ± 0:10	23:32 ± 0:09**	23:41 ± 0:10**	4.5	% Chance[b]	99/0/0	100/0/0	66/25/9
					Clin. inf.[c]	VL harmful	ML harmful	Unclear
Get-up time (h:min)					Difference[a]	52.1 (36.4; 67.8)	38.9 (26.4; 51.4)	13.2 (−4.0;30.4)
	7:24 ± 0:07	8:16 ± 0:07***	8:03 ± 0:07***	3.6	% Chance[b]	100/0/0	100/0/0	5/13/82
					Clin. inf.[c]	ML harmful	ML harmful	L beneficial
Time spent in bed (h:min)					% Difference[a]	2.5 (−3.1; 8.4)	−2.3 (−5.9; 1.3)	4.9 (1.7;8.2)
	8:32 ± 0:13	8:43 ± 0:05	8:19 ± 0:08	1.4%	% Chance[b]	64/23/13	5/26/69	97/3/0
					Clin. inf.[c]	Unclear	Unclear	VL beneficial
Actual sleep duration (h:min)					% Difference[a]	0.6 (−4.3; 5.7)	−4.7 (−7.5; −1.8)	5.5 (2.3;8.8)
	7:13 ± 0:11	7:15 ± 0:07	6:53 ± 0:09*,****	1.3%	% Chance[b]	39/36/25	0/3/97	98/2/0
					Clin. inf.[c]	Unclear	VL harmful	VL beneficial
Sleep latency (min)					% Difference[a]	25.4 (−20.1; 96.8)	45.0 (6.7;97.0)	−13.5 (−36;16.9)
	17 ± 2	23 ± 4	28 ± 6*	9.3%	% Chance[b]	72/16/12	95/4/1	10/24/'66
					Clin. inf.[c]	Unclear	ML harmful	Unclear
Sleep efficiency (%)					% Difference[a]	−1.9 (−3.4; −0.4)	−2.3 (−4.1; −0.6)	0.5 (−1.4;2.4)
	84.7 ± 1.3	83.1 ± 1.1	82.7 ± 1.6*	0.3%	% Chance[b]	2/2/96	1/2/97	59/16/25
					Clin. inf.[c]	VL harmful	VL harmful	Unclear
% Time spent moving					% Difference[a]	12.0 (6.5; 17.9)	8.7 (2.9; 14.9)	3.0 (−2.0; 8.3)
	14.1 ± 0.8	15.9 ± 1.0*	15.5 ± 1.1*	3.1%	% Chance[b]	99/1/0	94/6/0	49/48/3
					Clin. inf.[c]	VL harmful	L harmful	P harmful
Perceived fatigue (1–7)					% Difference[a]	2.8 (−2.4;8.30)	9.9 (0.2; 20.5)	−6.5 (−1.6; 16.2)
	4.2 ± 0.4	4.3 ± 0.4	4.5 ± 0.4*	3.0%	% Chance[b]	47/49/4	88/10/2	3/19/'78
					Clin. inf.[c]	P harmful	L harmful	L beneficial
Perceived sleep quality (1–7)					% Difference[a]	3.1 (−5.3; 12.2)	2.2 (−9.8; 15.8)	−0.8 (−12.1; 11.9)
	4.5 ± 0.3	4.5 ± 0.4	4.5 ± 0.4	3.0%	% Chance[b]	10/89/1	16/78/6	8/81/11
					Clin. inf.[c]	Unlikely	Unclear	Unclear

Each questionnaire item was rated on a scale from 1 to 7 (from best to worst in ascending order).
[a]Difference in mean.
[b]Percent chance that the true value is mechanistically or clinically substantially positive, trivial, or negative.
[c]Clinical inference.
*$P < 0.05$, different from BASE.
**$P < 0.01$, different from BASE.
***$P < 0.001$, different from BASE.
****$P < 0.05$, different from IT_{WBC}.
SWC, smallest worthwhile change, calculated at 0.3 × CV from 2 wk of follow-up during normal training; VL, very likely; ML, most likely; L, likely; P, possibly.

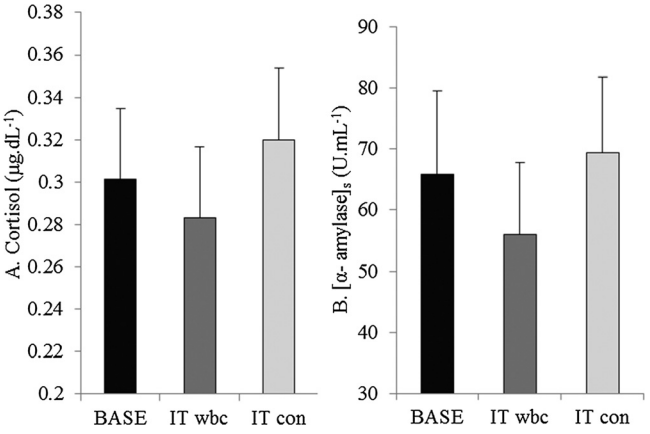

FIGURE 3—Fasted, waking [cortisol]$_s$ ($\mu g \cdot dL^{-1}$) (A) and [α-amylase]$_s$ ($U \cdot mL^{-1}$) (B).

(9,16). Recently, Hausswirth et al. (16) demonstrated the link between objectively measured changes in sleep quality and quantity and the development of the overreached state. They showed that well-trained male triathletes who became overreached after 3 wk of IT showed significant reductions in total sleep time and sleep efficiency, whereas triathletes who performed the IT protocol but were not overreached did not show any such changes. Furthermore, as sleep patterns returned to baseline values in the overreached athletes during the subsequent taper period, it appears that changes in objectively measured sleep quality may serve as a useful gauge for the actual state of fatigue of the athlete. Fietze et al. (9) found similar decreases in sleep quality over several weeks of IT in professional ballet dancers as those found in the synchronized swimmers. The mean sleep efficiency of both dancer and synchronized swimmer populations under baseline conditions resembled that reported in other elite female athletes by Leeder et al. (25) (81%, 85%, and 85%, respectively), and it appeared lower than the sleep efficiency of nonelite athletes (90%) (16) or healthy controls (88%) (25), evaluated with the same methods. This may suggest that the amount of physical and/or psychological stress experienced as a result of training at the elite level may affect sleep patterns and sleep quality.

Further intensifying the training load during the IT periods resulted in the degradation of several parameters of sleep quantity and quality. The decrease in total sleep quantity during IT_{CON} appeared to result from a combination of a significant shift toward a later bedtime, longer sleep latency, and more time spent awake after sleep onset, reflected in the decreased sleep efficiency. Despite maintaining a similar hourly training schedule throughout the protocol and reporting greater fatigue levels, completing very high intensity training sessions in the early evening may have affected their readiness to retire for bed during IT and their sleep architecture. Falling asleep normally occurs as sympathetic and hypothalamic–pituitary–adrenal (HPA) activity levels decrease, which is concomitant with an increase in parasympathetic activity and darkness-induced melatonin secretion by the pineal gland (15,40). Exercise stimulates both sympathetic and HPA activity in an intensity-dependent fashion (32), and a strenuous training session may cause sympathetic activity to remain elevated for several hours after exercise, disturbing the athlete's sleep quality (36). Furthermore, [α-amylase]$_s$ has emerged as a potential biomarker for sleep loss because it has been found to rise with sleep deprivation (16). In the present study, the decreased actual sleep duration and the correlations between increased waking [α-amylase]$_s$ and decreased sleep latency, sleep efficiency, and increased perceived fatigue lend support to this concept. From a practical standpoint, it may therefore be advantageous to provide more flexibility in the morning training schedules during IT periods to give the athletes the opportunity to at least attempt to maintain their total sleep duration to offset its reduced quality.

Interestingly, despite reporting increased fatigue during IT_{CON}, the swimmers' perceived sleep quality did not change. Hausswirth et al. (16) recently found a similar result in overreached triathletes, and studies performed on the general population have found poor agreement between perceived sleep quality and objective measures of sleep. Together, these findings stress the importance of obtaining objective measures to assess the quality of athletes' sleep during these highly fatiguing training periods, as detrimental changes in sleep patterns may point to the development of functional overreaching.

Effects of daily WBC use on early signs of fatigue. In light of the exercise and sleep-related signs of functional overreaching observed during IT_{CON}, optimizing recovery should be made a priority if IT periods are to be performed just before key international competitions. Although the effectiveness of WBC has now been demonstrated in a variety of short- and medium-term recovery timelines (i.e. ~1 to 24–76 h) (17,37,39), the present study showed that daily WBC use may be a worthwhile strategy in helping prevent fatigue accumulation in elite synchronized swimmers.

During the fixed-speed 200-m intervals, s1, s2, and s3, even though the HR and $[La^-]_{B400}$ response to each interval was reduced similarly during IT_{WBC} and IT_{CON}, RPE at the s3 speed was lower during IT_{WBC} than IT_{CON}, suggesting improved fitness, with reduced physical effort and perceived difficulty for a fixed workload. During the TT_{400}, the preserved $[La^-]_{B400}$, [α-amylase]$_{s400}$, and HR response to exercise, together with maintained performance from BASE, suggests that WBC helped offset the exercise-related signs of functional overreaching observed after IT_{CON}.

The daily WBC sessions may have improved the swimmers' tolerance to the training load in part by helping to preserve sleep quantity during this period of increased physical and psychological stress. Indeed, WBC use during IT exerted a *very likely moderate beneficial* effect on actual sleep duration compared with IT_{CON}, mainly via a *moderate* increase in wake-up and get-up times and by limiting the increase in sleep latency. It is possible that the strong influence of WBC on postexercise parasympathetic reactivation may have played a role in preserving these sleep parameters. We

recently demonstrated that WBC elicited a prompt parasympathetic reactivation at the cardiac level after a maximal exercise bout in elite synchronized swimmers (39), bringing vagal-related heart rate variability indices two- to fourfold higher than preexercise values. This can be explained by the intense cold stimulus applied to the skin causing an increased sympathetic nerve output to the periphery, evidenced by rising plasma norepinephrine concentrations (18,30). The resulting alpha-adrenergic–mediated vasoconstriction of peripheral vessels leads to a shift of blood volume toward the core, thereby triggering a baroreflex-mediated increase in vagal tone at the cardiac level (38).

Furthermore Al Haddad et al. (2) reported that male swimmers using cold-water immersion daily during a week of normal training displayed higher indices of parasympathetic activity in the morning and expressed improved sleep quality. WBC aiding the reduction of sympathetic cardiac modulation at the end of the evening training session, a few hours before sleep, may therefore promote relaxation and the onset of sleepiness; this could explain the preserved sleep latency and actual sleep duration, in turn preventing fatigue levels from rising over the course of IT and avoiding functional overreaching.

Other physiological effects of acute cold exposure that were not studied here may have participated in improving these swimmers' recovery and preventing signs of functional overreaching. The increase in circulating norepinephrine caused by WBC has also been hypothesized to play a role in reducing the inflammation and muscle damage to severe exercise because Pournot et al. (37) observed reduced plasma concentrations of proinflammatory cytokines and C-reactive protein, increased concentrations of anti-inflammatory cytokines, together with decreased muscle soreness. Furthermore, cold exposure induces the production of beta-endorphin, a neurotransmitter exerting analgesic effects and responsible for the sense of well-being, which could explain improved recovery sensations after WBC (37) or cold-water immersion (2). Future studies are needed to describe the mechanisms by which cryostimulation may help preserve sleep quantity and mitigate the appearance of excess fatigue during IT.

Lastly, it cannot be excluded that some of the beneficial effects observed during the IT_{WBC} period may have been influenced by a placebo effect, as there is no good way to blind subjects from cryotherapy. Recently, Broatch et al. (5) found that immersion in thermoneutral water, in which experimenters placed a placebo solution aiming to mislead subjects that this treatment was beneficial in recovery from high-intensity exercise, yielded similar improvements in markers of recovery compared with cold-water immersion. Furthermore, both the thermo-neutral placebo and the cold-water immersion were more effective than a thermo-neutral water immersion control treatment (with no solution added) in muscle strength recovery over 48 h, improving levels of perceived pain and readiness to exercise. Although many athletes may believe in the effectiveness of cold-water immersion in aiding physical recovery, as it has been thoroughly studied, the present study is the first, to our knowledge, to investigate the influence of WBC on objective sleep parameters in a sports training context. Therefore, it is unlikely that the synchronized swimmers had any specific expectations about the effects of WBC on sleep, specifically.

CONCLUSION

This study is the first to investigate the physiological and psychological response to typical IT periods performed by elite synchronized swimmers before their major international competitions, and it demonstrates that such periods result in signs of fatigue accumulation associated with the onset of the functionally overreached state. This study is also the first to evaluate the effectiveness of WBC as a recovery strategy in such a context. Daily WBC use during IT significantly improved the quality of the swimmers' recovery by preserving sleep quantity and preventing the increase in perceived fatigue observed during IT_{CON}. WBC use also limited the appearance of physiological signs associated with functional overreaching during maximal exercise, such as reduced sympathetic activation and lactate accumulation, and prevented the decrease in performance that occurred after IT_{CON}. Further research is needed to determine how regular WBC use during such periods may affect overall performance gains, in addition to its beneficial effects in reducing fatigue accumulation. In the meantime, our findings provide a first basis for recommending WBC use to elite athletes seeking to train intensely while reducing their risk of developing functional overreaching, as would be the case before major international competitions.

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