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Short-term Sleep Extension in Adolescent Swimmers: Real-world Crossover Findings on Sleep, Mood, and Performance

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Abstract: Objectives: To test whether short-term sleep extension affects sleep, mood, and swim performance in adolescent competitive swimmers under real-world training. Methods: A pragmatic within-group, two-period crossover compared Regular and Extended sleep during routine in-season training. Outcomes included device-based sleep (with HRV-derived staging), pool performance (50-m sprint; mean 10×50-m pace; 800-m time trial), post-set physiology, and mood (EFI). Primary inference focused on the within-subject Regular vs Extended contrast; three-phase (Preliminary/Regular/Extended) ANOVAs were descriptive. Results: Total sleep time increased with Extended vs Regular, confirming successful manipulation. Group-level pool performance did not improve across tests (all paired contrasts non-significant). Mood changes were small and non-significant. Physiological responses were largely unchanged; however, post-set blood lactate after the 10×50-m set was modestly lower with Extended (Holm-adjusted p = .035). Sleep architecture shifted: Deep sleep was lower and arousal indices higher under Extended. Conclusions: In adolescent swimmers, short-term sleep extension is feasible and increases sleep duration under real-world conditions but does not yield immediate gains in pool performance. A small reduction in post-set lactate and alterations in sleep architecture warrant cautious interpretation. Findings temper expectations for near-term performance benefits and motivate longer, individualized protocols with monitoring of achieved extension dose.

Keywords: Sleep Extension, Adolescent Athletes, Swimming Performance, Sleep Architecture, Mood, Crossover Design

1. Introduction

Sleep is a fundamental behavioral state essential for survival and well-being. For athletes, it plays a critical role not only in physical recovery but also in enhancing cognitive performance, reaction time, and decision-making. Adequate sleep is increasingly recognized as a vital pillar of athletic performance, supporting endurance and reducing injury risk. As noted by Krueger *et al.* (2008) and Simpson, Gibbs & Matheson (2017), the growing focus on sleep in high-performance sports highlights its significance as a key area of research.

Numerous studies have emphasized sleep's essential role in athletic recovery (Halson & Juliff 2017; Nédélec *et al.* 2015). The National Sleep Foundation recommends 8-10 hours of sleep per day for teenagers aged 14-17 and 7-9 hours per day for young adults aged 18 to 25. Research on sleep patterns has highlighted the significant impact of sleep duration on cognition, physical performance, mood, illness, and injury risk (Filipas *et al.* 2021; Hirshkowitz *et al.* 2015; Jarraya *et al.* 2014; Mah *et al.* 2011; Silva *et al.* 2021).

Despite these recommendations and findings, many athletes experience insufficient sleep and poor sleep quality (Lastella *et al.* 2015; Leeder *et al.* 2012). Studies involving athletes from different sports have shown that a significant percentage, often exceeding ~40%, report insufficient sleep (Mah *et al.* 2018). This highlights a widespread issue that requires attention within the athletic community. Sleep disturbances in athletes are attributed to a variety of factors, both non-sport and sport-specific. The latter include high training load, unfamiliar sleeping environments, early-morning training sessions, pre-competition anxiety, and long-haul travel, all of which can negatively affect both the quantity and quality of an athlete's sleep (Walsh *et al.* 2021).

Swimmers are especially vulnerable to sleep restriction and disturbances due to their early-morning training sessions (often before 08:00) and rigorous training schedules (Aloulou *et al.* 2021; Sargent, Halson, & Roach 2014). Sleep restriction occurs when individuals face conditions that limit their total sleep time below what is necessary for their daily requirements (Lowe, Safati, & Hall 2017). In studies comparing the sleep patterns of athletes from different sports, swimmers have been reported to have the shortest sleep duration and the highest sleep fragmentation index (Lastella *et al.* 2015; Lowe *et al.* 2017), indicating their unique challenges in achieving restful sleep.

In adolescent swimmers specifically, insufficient sleep and poor sleep quality are common and associated with daytime cognitive impairment and increased sleepiness (Biggins *et al.* 2019; Lastella *et al.* 2015; Sargent *et al.* 2014; Surda *et al.* 2019). In several cohorts, Epworth Sleepiness Scale scores of ≥11 have been reported, with swimmers showing among the highest values (Aloulou *et al.* 2021). Pragmatic approaches to address these issues typically combine modest bedtime adjustments with targeted sleep-hygiene routines that can be delivered within team environments. Sleep training courses are intended to enhance both the quality and quantity of athletes' sleep. These courses offer various techniques aimed at improving sleep hygiene, assisting in sleep, and extending sleep duration (Gwyther *et al.* 2022). Sleep hygiene strategies comprise a set of recommendations meant to foster healthy sleep habits by addressing lifestyle, behavioral, and environmental factors (Sateia *et al.* 2000). Typically, these strategies focus on sleep and wake cycles, pre-bedtime routines, optimizing the bedroom environment, minimizing exposure to electronic device-induced light, and managing caffeine consumption (Caia *et al.* 2018; Fullagar *et al.* 2016; O'Donnell and Driller 2017; Sargent *et al.* 2021; Vitale *et al.* 2019).

Despite a growing literature on sleep and performance, adolescent athletes remain under-represented. This group faces unique constraints (academic demands, biological changes, social pressures) that can limit sleep opportunity and complicate translation of behavioral change into performance. Consequently, there is a need for ecologically valid studies that embed short-term sleep-extension strategies within routine team training and evaluate both behavioral and performance outcomes. Accordingly, the present study focuses on competitive adolescent swimmers and tests whether a brief, real-world sleep-extension period increases nightly sleep duration and improves mood states, and whether such changes translate to commonly monitored pool-performance metrics. Daily subjective mood was evaluated using the Exercise-Induced Feeling Inventory (EFI; Gauvin & Rejeski, 1993). We anticipated a clear increase in total sleep time, possible small improvements in mood, and uncertain effects on performance over a short observation window.

2. Materials and Methods

2.1 Participants

This study commenced with a cohort of 22 participants. During the course of the study, five participants were excluded from the analysis due to absences exceeding 10% of the scheduled training sessions, which were attributed to injuries or illnesses. Consequently, the final dataset comprised 17 competitive adolescent swimmers (12 males and 5 females). The participants had an average age of 17.0 ± 0.80 years, stature of 176.0 ± 7.30 cm, body mass of 66.0 ± 6.90 kg, and body fat percentage of $11.62 \pm 5.00\%$. All participants were selected from a national-level training academy for young athletes. Several were national record holders in their age group, while others were national champions or medalists in both youth and adult categories. They had extensive competitive experience, including participation in international swimming events. Most swimmers began training at around age 9 and joined the intensive boarding program at approximately 14–15 years old.

Their weekly training schedule included 9 to 10 swimming sessions (approximately 2 hours per session, totaling 20–24 hours per week), along with four land-based fitness training sessions lasting one hour each. All participants were medically cleared for participation following routine health examinations conducted within one month prior to the study.

Before the intervention, all participants attended an educational session about the importance of sleep. They voluntarily agreed to participate in the study. Informed consent was obtained from both participants and their legal guardians. The study protocol was approved by the local institutional ethics committee. Details of the cross-over assignment and sleep-sequence procedures are provided under Study design and procedures.

2.2. Research Tools

In this study, the researchers employed five measurement tools as follows:

1 Swimming performance was assessed by measuring swim times over various distances using the Omega RC 21 electronic timing system (Vill, Switzerland), with a precision of 1/1000 seconds.

2 Heart rate during the tests was measured using the Polar Accurex Plus pulse monitor (Polar Electro, Woodbury, NY, USA).

3 Blood lactate concentration at the end of each test was measured using a portable Accusport device (Boehringer, Mannheim, Germany).

4 Sleep was evaluated via heart rate variability (HRV) analysis using Hypnocore technology. Nocturnal HRV was recorded using commercially available chest straps (Suunto, Finland), which measured both heart rate and electrocardiogram (ECG) data. Sleep stages were inferred from HRV rather than confirmed by lab-based recordings, which may reduce classification accuracy.

5 Subjective mood states were assessed daily using the Exercise-Induced Feeling Inventory (EFI; Gauvin & Rejeski, 1993), a validated self-report questionnaire commonly used in sports and exercise research. The EFI evaluates four dimensions of mood: revitalization, positive engagement, tranquility, and physical exhaustion. Participants completed the EFI questionnaire each morning throughout all phases of the study, rating their feelings on a 5-point Likert scale ranging from 0 ("do not feel at all") to 4 ("feel very strongly"). Higher scores indicated more positive mood states (for revitalization, positive engagement, and tranquility) or greater feelings of fatigue (for physical exhaustion). Mean scores for each mood dimension were calculated separately for the regular sleep and extended sleep conditions.

HRV reflects the physiological variation in time intervals between successive heartbeats, known as RR intervals, where "R" denotes the peak of the ventricular depolarization complex, the QRS complex, on the ECG. HRV serves as an indicator of autonomic nervous system (ANS) activity, particularly during sleep. Based on this concept, a specialized software (HC1000P) developed by Hypnocore was used to analyze sleep structure and efficiency by interpreting HRV patterns. This method for assessing sleep quality and detecting sleep disturbances using HRV analysis has been validated in previous studies (Decker et al. 2010). In validation work, ECG-derived sleep architecture from this system has shown good agreement with polysomnography for estimates of total sleep time, sleep efficiency, and the detection of wake and deep-sleep episodes, with more modest precision for fine-grained stage proportions (Decker et al., 2010). In line with these properties, the present analysis emphasized within-athlete contrasts in total sleep time and arousal indices rather than clinical staging, and deep-sleep and arousal metrics were interpreted cautiously. Recent findings suggest that while sleep extension may initially increase sleep fragmentation, it often stabilizes after an adaptation period, restoring normal sleep architecture (Van Dongen *et al.* 2004; Zhang *et al.* 2021).

2.3 Sleep and Assessment Procedure

2.3.1 The research was conducted in three stages, as follows

1 ***Preliminary phase:*** During this stage, all participants maintained their usual routines for two weeks. Performance evaluations were conducted using a series of standard swimming tests (detailed below), administered twice: two weeks prior to the intervention and again immediately before its onset. This stage was used to assess baseline physical fitness and to detect any natural variation in swimming performance, physiological responses, or total sleep duration prior to the intervention.

2 ***Intervention Phase 1 (two-period cross-over, within groups):*** Participants were divided into two groups. One group continued with their habitual nightly sleep duration (regular sleep condition), while the other group was instructed to extend their sleep each night (extended sleep condition) for two weeks. At the end of this phase, all participants completed the same series of swimming tests.

3 ***Intervention Phase 2 (cross-over):*** In the subsequent two-week period, the groups switched conditions. The group that previously maintained regular sleep now adopted the extended sleep schedule, while the group that had previously received extended sleep returned to their regular sleep pattern. At the end of this phase, the swimming tests were repeated. No formal washout period was implemented between phases, and potential period and carryover effects were considered in the statistical analysis.

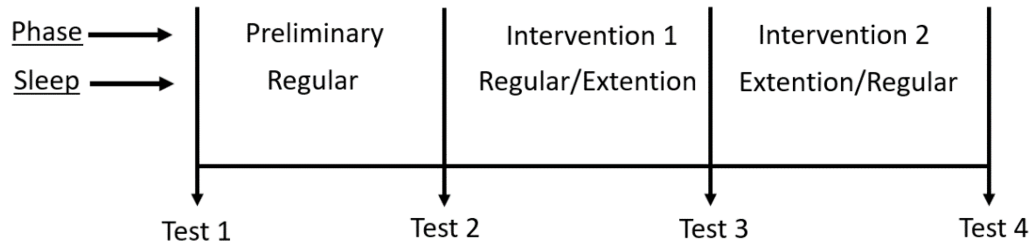

Figure 1. Schematic description of the study across phases and sleep conditions.

A schematic overview of the three-phase research procedure is presented in Figure 1.

Throughout all three conditions of the study, participants wore heart rate monitors during sleep. The devices were worn from the time the lights were turned off until the participants woke up in the morning. Heart rate data recorded overnight were transferred to a computer each morning. Subsequently, sleep duration and structure were analyzed using HC1000P software. Sleep variables were interpreted and analyzed individually for each participant.

The following sleep metrics were derived from the HRV analysis:

- ***Total Sleep Time (TST):*** The total duration of sleep per night.
- ***Slow-Wave Sleep Time (SWST):*** The cumulative time spent in deep sleep stages (Stages 3 and 4, non-REM).
- ***Rapid Eye Movement Time (REMT):*** The total duration of REM sleep.
- ***Number of Awakenings:*** The number of discrete awakenings during the night, each lasting at least 15 seconds.
- ***Arousal Index:*** The average number of arousals per hour of sleep (brief wake episodes lasting 3–15 seconds). Reference values vary by age, scoring criteria, and method; lower densities generally indicate fewer arousals.

2.4 Intervention Sleep Phase

During the first two weeks of the intervention, one group had lights out at 22:30, while the other group was instructed to go to bed at 21:30. Wake-up times remained unchanged: 05:45 on Sundays, Tuesdays, and Thursdays (for morning training sessions), and 06:50 on Mondays and Wednesdays. Bedtime and lights-out schedules were monitored daily by residential staff and researchers based on a predetermined protocol.

At the end of the first two-week period, the groups switched conditions. The group that had previously gone to bed at 22:30 was now instructed to follow the extended sleep schedule (21:30), while the group that had previously followed the early bedtime returned to their usual 22:30 routine (regular sleep condition). This cross-over period lasted an additional two weeks, after which the test battery was administered again.

Participants left the residential facility on Friday afternoons and returned on Sundays. They were not involved in training activities on Saturdays. To maintain consistency in sleep patterns during weekends, participants were instructed to avoid sleeping more than 10 hours per night and to refrain from daytime naps. Although sleep monitoring continued on Friday nights for control purposes, data from those nights were excluded from the formal analysis.

2.5 Performance Assessments

Swimming performance was evaluated using standard tests commonly utilized in competitive swimming settings. These assessments were administered routinely throughout the training season to monitor athletes' fitness levels and training adaptations. The tests selected for this study aimed to assess changes in speed, speed endurance, aerobic capacity, and swimming efficiency. All performance tests were conducted at 5:00 PM on the same days of the week to control for circadian variation. The specific tests included:

- ***Test 1:*** 50-Meter Maximal Sprint: Swimmers performed a 50-meter sprint at maximal effort. This test primarily engaged anaerobic energy systems (ATP-CP and glycolytic pathways).
- ***Test 2:*** 10×50 m Freestyle Intervals: Swimmers completed ten 50-meter repeats in freestyle with 30-second rest intervals, at a

pace slightly above each swimmer's preseason anaerobic-threshold pace, determined from routine squad testing at the start of the year and coach records, not from laboratory assessment during the study. This test combined anaerobic and aerobic energy systems.

- ***Test 3:*** 800-Meter Freestyle Swim. Athletes swam 800 meters continuously at each swimmer's preseason anaerobic-threshold pace, determined from routine squad testing at the start of the year and coach records, not from laboratory assessment during the study. This test primarily evaluated aerobic endurance.
- ***Test 4:*** Stroke Count Efficiency. The number of stroke cycles was recorded during the 50-meter sprint (Test 1) and during the 10×50 m set (Test 2). A lower number of cycles per 50 meters was considered indicative of greater swimming efficiency (one stroke cycle was defined as a complete right-arm and left-arm movement).

Tests 1 and 2 were conducted on the same day following a standardized warm-up, with approximately one hour of rest between them to ensure full recovery. Test 3 was conducted on a separate day. Test 4 was embedded within the execution of Tests 1 and 2.

At the end of each test, blood lactate concentrations were measured, and heart rate was documented. All assessments were conducted under regular training conditions. Aside from the manipulated sleep schedules, all other variables, including diet, daily routines, and training loads, were held constant between groups.

2.6 Study design and procedures

Participants were randomly assigned to two groups for the purpose of comparing two weeks of extended sleep to regular sleep. One group was instructed to increase their nightly sleep duration by approximately one hour during the first two weeks, while the second group did so during the subsequent two weeks. Based on their sleep schedules, participants were categorized into two conditions: regular sleep and extended sleep. To ensure consistency in sleep behavior and minimize mutual influence, participants were also randomly assigned to separate sleeping rooms. Background characteristics (e.g., gender, age, height, weight, and body composition) were summarized using descriptive statistics (means and standard deviations).

2.7 Data Collection and Analysis

All data were analyzed using the SPSS software package (version 25; SPSS Inc., Chicago, IL, USA). Primary inference used repeated-measures ANOVA tailored to the two-period cross-over design, with within-subject factors of condition (extended vs. regular) and period (1 vs. 2), and a between-subject factor of sequence (Extended→Regular vs. Regular→Extended). The main effect of condition was evaluated while inspecting period, sequence, and their interactions with condition (e.g., condition×period, condition×sequence) to screen for potential carryover. Period and sequence effects were tested and were non-significant. Primary inferential analyses were restricted a priori to TST, Deep sleep (%), Total arousals, and the arousal index to limit multiplicity; other sleep variables are reported descriptively. When sphericity assumptions were relevant, Greenhouse–Geisser corrections were applied and adjusted degrees of freedom are reported. Planned paired contrasts were conducted where appropriate with family-wise control (Holm). Effect sizes are reported as partial η^2 for ANOVA effects and Hedges' g (with 95% confidence intervals) for paired contrasts. Two-tailed $\alpha = .05$. In addition, repeated-measures ANOVA summaries were used to examine differences across the three phases (preliminary, regular sleep, extended sleep) for descriptive context, while inference focused on the cross-over factors described above.

3. Results

Table 1 presents mean ± SD values for sleep variables under Regular and Extended sleep. Total sleep time (TST) was significantly longer during Extended (M = 411.24, SD = 69.34 min) than Regular (M = 369.83, SD = 71.47 min), p = .030. Deep sleep (%) was lower during Extended (M = 25.44, SD = 6.03) than Regular (M = 29.00, SD = 8.56), p = .040. Total arousals and the arousal index were higher during Extended, p = .036 and p = .045, respectively. No significant differences were observed for SWST (min), REM sleep time (min), REM sleep (%), or number of awakenings per night. These findings confirm that the sleep-extension manipulation was successful and that it altered sleep architecture and arousal indices (Table 1).

Table 1. Sleep variables under Regular vs Extended sleep (mean ± SD; n = 17)

Variable	Regular (Mean ± SD)	Extended (Mean ± SD)	F(1,16)	p (Holm-adjusted)
Total sleep time (TST, min)	369.83 ± 71.47	411.24 ± 69.34	5.67	p = .030*
Slow-wave sleep time (SWST, min)	110.95 ± 22.43	109.43 ± 23.18	n/a†	n/a†
Deep sleep (%)	29.00 ± 8.56	25.44 ± 6.03	4.98	p = .040*
REM sleep time (min)	56.06 ± 25.14	63.87 ± 19.95	n/a†	n/a†
REM sleep (%)	13.20 ± 5.01	14.14 ± 3.37	n/a†	n/a†
Number of awakenings (count)	9.97 ± 6.19	10.80 ± 4.76	n/a†	n/a†
Total arousals (events)	63.54 ± 26.71	78.74 ± 25.19	5.23	p = .036*
Arousal index (events·h⁻¹)	12.29 ± 3.16	13.65 ± 3.51	4.75	p = .045*

Note. Values are mean ± SD. Statistics are from a repeated-measures ANOVA with a within-subject factor Condition (Regular vs Extended); df = 1, 16. Reported p-values are Holm-adjusted across the a priori outcomes (TST, Deep sleep %, Total arousals, Arousal index). Variables marked with † are descriptive only (no inferential test). *p < .05 after Holm adjustment. TST = total sleep time; SWST = slow-wave sleep time; Arousal index in events·h⁻¹.

Table 2. Physiological variables across preliminary, regular sleep, and extended sleep assessments (mean ± SD, n = 17)

Physiological variable	Preliminary (M ± SD)	Regular sleep (M ± SD)	Extended sleep (M ± SD)
Blood lactate after 50 m sprint (mmol·L⁻¹)	8.00 ± 2.00	7.10 ± 2.00	7.30 ± 2.20
Avg. heart rate during 10×50 m (bpm)	160.00 ± 8.00	160.00 ± 12.00	160.00 ± 10.00
Blood lactate after 10×50 m (mmol·L⁻¹)	5.60 ± 2.70	4.40 ± 2.10	4.00 ± 2.50*
Heart rate after 800 m (bpm)	164.00 ± 10.00	160.00 ± 14.00	165.00 ± 9.00
Blood lactate after 800 m (mmol·L⁻¹)	4.60 ± 1.70	3.70 ± 1.00	3.80 ± 1.70

* Significant paired difference (Regular vs Extended), Holm-adjusted p = .0352.

Note: Omnibus ANOVA values were used descriptively; primary inference used within-subject contrasts between Regular and Extended as specified in Statistical Analysis.

Table 2 summarizes heart-rate and blood-lactate responses across the Preliminary, Regular, and Extended phases. No overall differences were detected; however, the paired Regular→Extended contrast showed a modest reduction in post-set blood lactate after the 10×50-m set (Holm-adjusted p = .0352).

Primary performance outcomes did not differ between Regular and Extended sleep. Table 3 summarizes 50-m sprint time, mean 10×50-m pace, 800-m time, and stroke-cycle counts. All paired contrasts were non-significant. Individual responses varied across swimmers.

Figure 2 displays paired 800-m times for each swimmer under Regular and Extended sleep, with within-subject lines connecting conditions. Responses were heterogeneous, with improvements in some athletes, little or no change in others, and occasional declines

Table 3. Swim performance and efficiency — Regular vs Extended sleep (n = 17)

Measure	Regular — Mean ± SD	Extended — Mean ± SD	Δ (Ext−Reg)	%Δ
50-m time (s)	28.55 ± 2.55	28.56 ± 2.48	0.01	0.04%
10×50-m mean pace (s)	32.78 ± 2.36	33.10 ± 3.17	0.32	0.98%
800-m time (s)	592.3 ± 30.5	592.0 ± 31.0	−0.30	−0.05%
Stroke cycles — 50 m (count)	20.96 ± 2.91	21.96 ± 2.44	1.00	4.77%
Stroke cycles — 10×50 mean (count per 50 m)	15.83 ± 1.76	16.16 ± 2.07	0.33	2.08%

Note. Values are mean ± SD. Δ = Extended − Regular; %Δ = (Extended − Regular)/Regular×100. Paired contrast (Regular vs Extended) was performed for all measures; all p > .05 (ns).

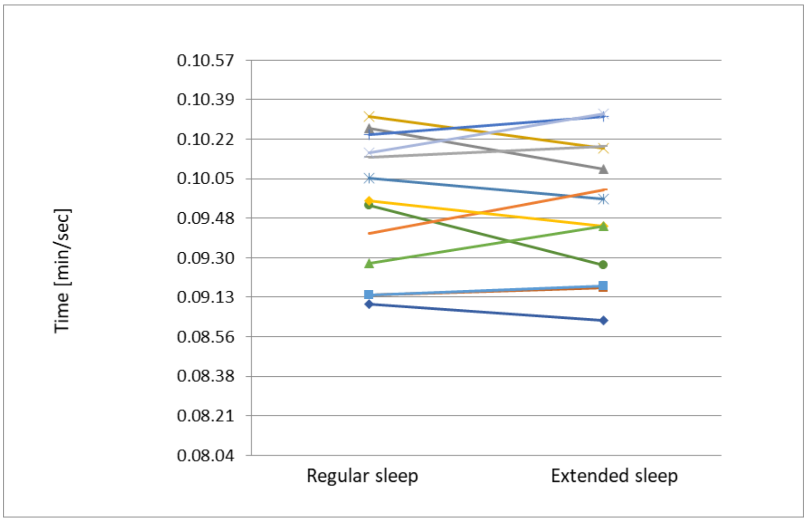

Figure 2. Individual changes in 800-meter swim performance from regular sleep to extended sleep conditions.

Table 4. Mood states (EFI) under regular and extended sleep conditions (mean ± SD, n = 17)

Mood State Dimension	Regular Sleep (M ± SD)	Extended sleep (M ± SD)
Revitalization	2.61 ± 0.65	2.68 ± 0.61
Positive Engagement	3.00 ± 0.75	3.23 ± 0.62
Tranquility	3.10 ± 0.80	3.33 ± 0.55
Physical Exhaustion	3.14 ± 0.55	3.15 ± 0.91

Note. Primary inference used paired contrasts (Regular vs Extended); all p > .05 (Holm-adjusted). Repeated-measures ANOVA summaries across phases were descriptive only. EFI subscales were scored 0–4; higher scores reflect more of the named state (higher Physical Exhaustion = more exhaustion).

Similar individual variability was observed in other swim tests under both sleep conditions, highlighting the inconsistency in participants' physiological and performance responses to sleep extension.

Mood states were assessed daily using the Exercise-Induced Feeling Inventory (EFI), which evaluates four dimensions: revitalization, positive engagement, tranquility, and physical exhaustion. Table 4 presents the mean ± SD values for each dimension under regular and extended sleep conditions. No statistically significant differences were found for any EFI dimension (paired Regular vs Extended; all p > .05, Holm-adjusted). However, a consistent trend toward improved subjective mood was observed during the extended sleep phase, with higher mean values reported for revitalization, positive engagement, and tranquility, while physical exhaustion remained stable across both conditions.

4. Discussion

This study examined whether a moderate sleep extension of approximately 42 minutes per night over two weeks would influence swimming performance and sleep quality among elite adolescent swimmers. While most studies in the literature have focused on very short, acute interventions ranging from one to three nights (e.g., Mah *et al.* 2011), the current research explored a more ecologically valid and feasible sleep intervention relevant to adolescent athletes. Given that sleep plays a central role in recovery, performance, and general well-being (Walsh *et al.* 2021), identifying effective ways to extend sleep among youth athletes is of growing importance.

The findings indicated that this degree of sleep extension increased total sleep time but did not translate into measurable gains in pool performance across 50 m, mean 10×50 m, and 800 m tests. Heart-rate responses were not meaningfully altered. However, post-set blood lactate after the 10×50 m set was lower under the extended-sleep condition (Holm-adjusted $p = .035$). This pattern suggests a modest shift consistent with improved recovery or reduced glycolytic contribution at the same external workload. Concurrently, sleep architecture changed. Deep sleep was lower during extended sleep, and both total arousals and the arousal index were higher. Taken together, these patterns support the feasibility of sleep extension but caution against expecting short-term performance enhancement in well-trained adolescents.

These results are consistent with previous research involving sleep restriction and brief sleep manipulations in athletes (e.g., Plyley *et al.* 1987; Skein *et al.* 2011). They also qualify conclusions from broader syntheses. For example, Cunha *et al.* (2023) concluded that extending sleep by approximately 46–113 minutes per night over 3–49 nights tended to improve physical and cognitive performance, particularly in habitually short-sleeping athletes. Our data sit at the low end of that nightly dose (about +42 minutes) over a short window, which may be insufficient to shift performance in already well-trained swimmers. Likewise, Zhang *et al.* (2021) found decrements with partial sleep deprivation in adolescent athletes. This reinforces the cost of insufficient sleep but does not guarantee acute gains when sleep is only modestly extended.

An important observation in this study is the marked inter-individual variability in responses to sleep extension. As shown in Figure 2, some swimmers improved, others showed little or no change, and a few performed worse under extended sleep. This pattern is consistent with prior reports of pronounced intra-individual and inter-individual variability in sleep and performance responses among athletes (Van Dongen *et al.,* 2004; Kemp et al., 2023). Group means therefore mask meaningful person-level differences, underscoring the need for responder-focused strategies, including identifying likely responders, quantifying the achieved extension dose (ΔTST, min/night), and closely monitoring adherence and response (see Figure 2 and Table 3). These findings caution against one-size-fits-all prescriptions and support individualized sleep planning within training cycles. Despite aiming for a one-hour sleep extension, the average increase was approximately 41–42 minutes. This demonstrates the difficulty of modifying adolescent sleep behavior. The partial compliance mirrors findings by Sadeh, Gruber, and Raviv (2003) and is consistent with classic work by Carskadon *et al.* (1998) and Crowley, Acebo, and Carskadon (2007), which describe adolescents' delayed circadian phase and difficulty initiating sleep earlier. More recent evidence (Beattie *et al.* 2015; Lo *et al.* 2016) reinforces these challenges. Biological rhythms, early training schedules, and social pressures reduce feasibility. In this boarding-school context, swimmers juggled early-morning practice with late academic demands, shared dormitory rooms, and evening social activities, which limited how much earlier they could realistically fall asleep. Even when athletes attempted to advance bedtime, homework, screen use before lights-out, and roommates' schedules often delayed sleep onset and truncated the achievable extension. Accordingly, delaying wake-up times when feasible, or periodizing sleep extension during lower-load weeks, may be more effective than consistently advancing bedtime.

The paradoxical pattern in sleep architecture, namely lower Deep % with higher arousals despite longer sleep, is compatible with short-term fragmentation during adaptation to extended sleep (Cho *et al.* 2015; Devoto *et al.* 1999; Sadeh *et al.* 2003; Webb and Agnew 1975). Sleep continuity may normalize over longer interventions (Minges and Redeker 2016). Although these changes did not enhance performance over two weeks, they help explain how sleep extension may initially redistribute architecture and recovery processes.

Although cognitive performance was not directly assessed in this study, prior work shows that insufficient sleep can impair attention, decision-making, and reaction time, all of which matter for athletic success (Cunha *et al.* 2023; Mah *et al.* 2011).

In summary, a modest and feasible sleep-extension period increased total sleep time without improving swim performance over two weeks. Post-set blood lactate after 10×50 m decreased modestly, and sleep architecture showed short-term fragmentation. These data favor individualized, longer, and potentially higher-dose sleep-extension strategies. Integrating responder identification and objective monitoring may clarify the relationship between dose and response and help realize practical benefits in adolescent swimmers.

5. Conclusions

Modest nightly sleep extension over two weeks increased total sleep time in elite adolescent swimmers by approximately 40–45 minutes but did not translate into detectable improvements in pool performance or swimming efficiency in this real-world crossover design. Post-set blood lactate after the 10 × 50 m set was modestly lower with extended sleep, and sleep architecture showed short-term fragmentation, with reduced deep sleep and more arousals, that appeared to normalize over time. Together, these findings suggest that brief, ecologically implemented sleep-extension blocks are feasible in competitive youth programs and can modify physiological markers of exertion, yet may be insufficient in duration or dose to produce robust gains in race-pace performance. The modest increase in sleep time, substantial inter-individual variability, and total sleep remaining below the ~9 hours typically recommended for adolescents likely constrained the impact on swimming outcomes. Overall, the study supports prioritizing sleep as a manageable recovery strategy within the training process while setting realistic expectations that short-term extensions alone may not yield immediate performance breakthroughs in well-trained adolescent swimmers. Future research should evaluate longer and higher-dose sleep-extension protocols, test implementation during different phases of the training cycle, and examine broader outcomes such as cognitive function, injury risk, and psychosocial well-being.

5.1 Perspectives/Practical Applications

Modest nightly sleep extension over two weeks increased total sleep time but did not improve pool performance or efficiency in elite adolescent swimmers. Given the marked inter-individual variability, coaches should favor personalized sleep strategies over one-size-fits-all protocols and monitor the achieved dose of extension and adherence in each athlete. When feasible, later wake times or schedule adjustments may be more practical than earlier bedtimes, aligning with adolescents' delayed circadian phase. Implement routine tracking of nightly sleep duration, perceived sleep quality, mood, and recovery alongside training logs to identify both potential responders and athletes who struggle to adhere. Simple tools such as weekly sleep diaries, brief morning ratings, or non-invasive wearables can help coaches and support staff verify that additional sleep is being achieved and adjust goals accordingly. From a practical standpoint, coaches working with adolescent swimmers and other youth athletes can embed short "sleep-extension blocks" within the season, coordinating with parents and teachers where possible to relax early-morning demands during these periods. Clear sleep-hygiene guidelines should be provided, including reducing evening screen exposure, maintaining consistent bed and wake times, limiting late-day caffeine, and optimizing dark, quiet sleeping environments in dormitories or at home. Future work should test longer and higher-dose protocols under real-world conditions and broaden outcomes beyond time-based pool measures to include strength, psychological state, recovery metrics, and brief neurocognitive assessments (e.g., psychomotor vigilance, go/no-go).

5.2 Limitations

This study has several limitations. First, it used an ecologically valid, two-period within-subject crossover that prioritized the Regular versus Extended contrast while screening for period and sequence effects. A formal washout was not implemented, so residual carryover from the first phase cannot be fully ruled out even though period/sequence were examined. In practical terms, swimmers transitioned directly from one condition to the other within their usual in-season schedule, so physiological and behavioral adaptations acquired in the first phase may have persisted into the second. Consequently, the within-subject Regular vs Extended contrast should be interpreted as conservative, and small or delayed effects of sleep extension may have been attenuated by residual carryover.

Second, sleep staging was inferred from HRV-based wearable metrics rather than polysomnography. Stage-classification accuracy can vary across devices and contexts, which warrants caution when interpreting Deep sleep and arousal metrics. Nevertheless, prior validation work indicates that such ECG-derived systems capture night-to-night changes in sleep duration and fragmentation with reasonable fidelity compared with polysomnography (Decker et al., 2010), supporting their use in pragmatic field studies of adolescent athletes when full laboratory monitoring is not feasible.

Third, the achieved sleep-extension dose was modest at approximately 42 minutes per night over two weeks, whereas the protocol targeted an additional 60 minutes. Total sleep time remained below the ~9 hours typically recommended for adolescents. Partial adherence and the short duration likely limited the potential to shift performance in well-trained swimmers.

Fourth, the sample size was modest. This reduces precision and increases uncertainty around small effects and potential interactions.

Fifth, hormonal and cognitive outcomes were not assessed. As a result, potential benefits outside time-based pool performance could not be evaluated.

Finally, participants were adolescent athletes residing in a structured boarding-school environment. While this setting facilitated some control over routines, academic demands and social factors may have influenced sleep and training. Caution is therefore needed when generalizing these findings to other populations such as adult or recreational athletes and to different competitive contexts.

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Author Contributions

Yossi Haleva: Methodology, Formal analysis, Writing-original draft, Writing-review and editing. Aya Ekshtein: Methodology, Formal analysis, Investigation. Leonid Kaufman: Investigation. Eyal Shargal: Supervision, Writing-review and editing. Yoav Meckel: Methodology, Supervision. All authors have read and agreed to the published version of the manuscript.

Informed Consent

Written consent was obtained from the participant before the study began.

Ethics Approval

Approval for this study was sought from IRB.

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