# Influence of menstrual cycle phase on sleep and recovery following high- and low-intensity training in eumenorrheic endurance-trained women: the FENDURA project.

Original Investigation


Madison Y. Taylor*[1], Maria Hrozanova*[2,3], Liv Nordengen[3], Øyvind Sandbakk[1,3], John O. Osborne[1], Dionne A. Noordhof[3]

*shared first authors

## Affiliations

1. School of Sport Sciences, UiT The Arctic University of Norway, Tromsø, Norway
2. Department of Public Health and Nursing, Norwegian University of Science and Technology, Trondheim, Norway
3. Department of Neuromedicine and Movement Science, Centre for Elite Sports Research, Norwegian University of Science and Technology, Trondheim, Norway

**Corresponding Author:**

Madison Y. Taylor

School of Sport Sciences

UiT- The Arctic University of Norway

madison.taylor@uit.no



SUBMISSION TYPE: Original Investigation
PREFERED RUNNING HEAD: Effect of menstrual cycle on recovery
ABSTRACT WORD COUNT: 250 words
TEXT ONLY WORD COUNT: 3286 words
NUMBER OF FIGURES AND TABLES: 2 tables, 4 figures

# ABSTRACT

**PURPOSE.** To investigate the influence of menstrual cycle (MC) phase on objective sleep and perceived recovery following high- (HIT) and low-intensity training (LIT) in endurance-trained women.

**METHODS.** Fifteen naturally menstruating, endurance-trained women completed standardized HIT and LIT sessions during the early follicular (EFP), ovulatory (OP) and mid luteal (MLP) phases of two MCs. Overnight sleep was monitored using a Somnofy sleep monitor after each training session and perceived recovery was assessed after 24 hours using self-report scales. MC phases were determined using the three-step method, and non-eumenorrheic MCs were retrospectively excluded from analysis.

**RESULTS.** MC phase had a main effect on wake after sleep onset ($p \leq 0.001$), with higher values in MLP (33±22 min) than EFP (22±19 min, $p=0.043$) and OP (14±9 min, $p=0.001$), sleep efficiency ($p=0.033$), with lower values in MLP (87±6%) than OP (90±8%, $p=0.047$), and light sleep ($p=0.023$) with higher values in MLP (59±6%) than EFP (54±7%, $p=0.037$). Session type had a main effect on perceived recovery ($p<0.018$) and perceived muscle soreness ($p=0.007$), indicating lower perceived recovery and higher perceived muscle soreness following HIT compared to LIT ($p<0.001$, $p=0.018$ respectively). No interactions were found between MC phase and session type for any of the measured variables.

**CONCLUSIONS.** Objective sleep quality, but not perceived recovery, was influenced by MC phase, as indicated by small impairments to multiple indices of objective sleep during MLP. There were no interactions between MC phase and session type, indicating that the effect of the MC on sleep and recovery are consistent regardless of session type.


KEY WORDS: females, sex hormones, estrogen, progesterone, fatigue, training load, endurance training

## INTRODUCTION

The increased participation of women in sport necessitates systematic training strategies that consider the nuances of female physiology.[1,2] Well-designed training programs seek to balance training-induced stimuli with adequate recovery, in order to maximize adaptations while avoiding states of excessive fatigue (i.e., nonfunctional overreaching) and injury.[3] Recovery refers to the physiological and psychological processes necessary for cognitive, muscular and metabolic restoration.[3] An athlete's recovery status can be monitored and assessed through subjective self-report questionnaires and/or objectively, for instance by monitoring sleep.[3,4] Together these markers provide an indication of an athlete's biopsychosocial balance and may be used to make adjustments to training load as necessary.[4] However, most of the literature on sleep and recovery is based on male-centric study designs, which leaves a clear knowledge gap regarding female-specific factors, such as the effect of the menstrual cycle (MC).[5,6]

Naturally menstruating women experience cyclical hormonal fluctuations across the MC. The MC can be divided into several phases, characterized by the concentration of estrogen and progesterone, i.e., the early follicular phase (EFP), ovulatory phase (OP), and mid luteal phase (MLP) (Figure 2). Studies in trained[7,8] and untrained[9-11] women have suggested that sleep may vary across the MC, with more sleep disturbances generally reported around menstruation or in the luteal phase.[12,13] Sleep plays an essential role in the rejuvenation of many recovery-enabling functions (i.e., cognition, immune, metabolic, musculoskeletal repair, etc.), making it particularly relevant for athletic development and recovery.[3,14,15] In addition to sleep, subjective markers of mood, motivation, and fatigue are frequently used to provide an indication of an athlete's perceived recovery status.[3] While limited research is available, lower mood, motivation, and readiness to train, have also been reported in the luteal phase in athletic women. [16-18] In contrast to the aforementioned studies, no effect of MC phase on sleep[11,19] as well as indications of impaired sleep and recovery in the follicular phase[7,20] have also been reported. The scarcity of female-athlete specific data, together with lack of consensus in the available literature, has prompted repeated calls for more high-quality research initiatives in this area. [6,21,22]

The current literature is limited by multiple factors. First, biological confirmation of MC phases (i.e., detection of ovulation and/or serum hormone analysis) has been underutilized in favor of calendar-based counting methods.[23] This approach leads to inconsistencies in the identification of MC phases and the unintentional inclusion of participants with abnormal hormonal profiles. [21] Second, most studies examining the effect of the MC on sleep compared healthy controls to a unique group of interest (e.g., severe menstrual pain, peri- or post-menopausal).[12] Sleep in athletes is influenced by various athlete-specific factors, such as high training loads, early morning/late night training, and mental strain,[15,24,25] precluding the generalizability and comparability of sleep outcomes from the general population to athletic populations. Finally, higher daily training loads have been shown to negatively influence recovery status in athletes, indicated through changes in sleep quality, mood, muscle soreness, and fatigue.[4,24] However, it remains unclear if this relationship is further moderated by exercise intensity and/or the MC.

To address the current gaps in the literature, the present study utilized a validated at-home sleep monitor and self-report questionnaires to assess sleep and perceived recovery status in three MC phases (EFP, OP, MLP) following a standardized high-intensity training (HIT) or low-intensity training (LIT) session. The aim was to investigate the influence of MC phase on objectively measured sleep and perceived recovery status following HIT and LIT in eumenorrheic endurance-trained women.

## METHODS

**Participants.** Naturally menstruating, endurance-trained women were recruited through sporting organizations, clubs and social media. The inclusion criteria were: 1) reported having a regular MC (cycle length between 21 and 35 days); [21] 2) had not used hormonal contraceptives for at least three months prior to enrollment; [21] 3) aged 17–40 years. In order to attract trained individuals with stable training loads the following criteria were included: 4) trained in an endurance sport ≥5 h per week; and 5) performed ≥1 HIT session per week, for the past 3 months. Participants were ineligible to participate if there was evidence of a menstrual disturbance, injury, illness, or had given birth within the past 12 months.[21]

Of the 23 participants that enrolled, 15 were included in the final analyses (Figure 1). Participants were classified as trained (tier 2, n=11) and highly trained (tier 3, n=4).[26] The mean ± SD age, body mass and peak oxygen uptake ($VO_{2peak}$) of the participants were 32 ± 5 years, 62 ± 7 kg, and 54.8 ± 5.2 $mL{\cdot}kg^{-1}{\cdot}min^{-1}$, respectively.

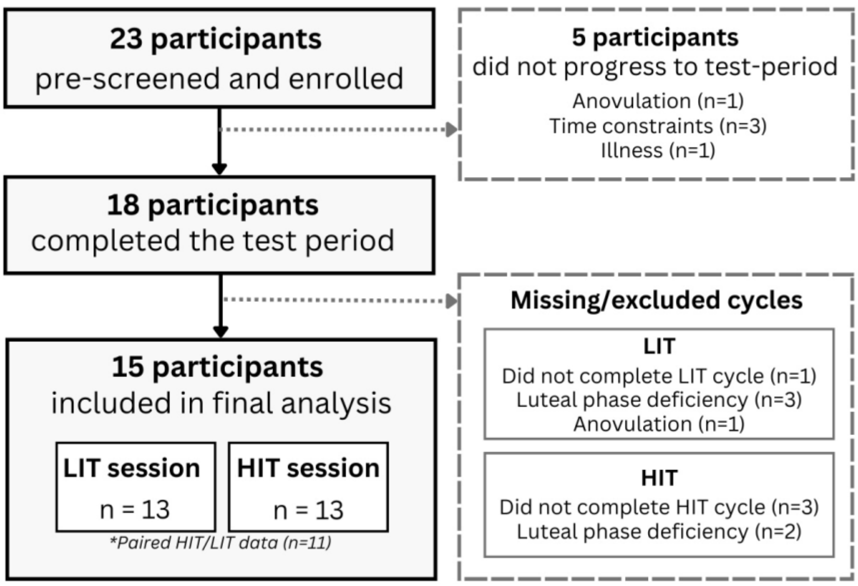


**Figure 1.** Participant inclusion flow chart.

**Study design.** During the lead-in period, participants tracked menstrual function for up to two MCs and completed a familiarization session in the laboratory. The test-period was conducted across two MCs. Participants visited the laboratory during the EFP (day one to four of the MC), OP (within 36 hours of a positive ovulation test) and MLP (seven to nine days following a positive ovulation test) to complete a supervised HIT or a LIT session. A counterbalanced, cross-over design was used, in which participants completed one MC of either HIT or LIT testing before moving on to the other session type in the second cycle (Figure 2). Exercise modality (running, n=13 or cycling, n=2) was self-selected upon enrollment and maintained throughout the test-period. Following each session, overnight sleep was recorded with a Somnofy sleep monitor (Somnofy SM-100 Research Edition, Vitalthings AS, Trondheim, Norway) and perceived recovery status was reported via the Recovery Status Questionnaire 24-h post-session (Figure 3).

The present study was part of the Female Endurance Athlete (FENDURA) project. The study was pre-approved by the Norwegian Social Science Data Services (NSD, 955558) and performed according to institutional ethical requirements. All participants were given written information about the study and provided written informed consent before the start of the study.

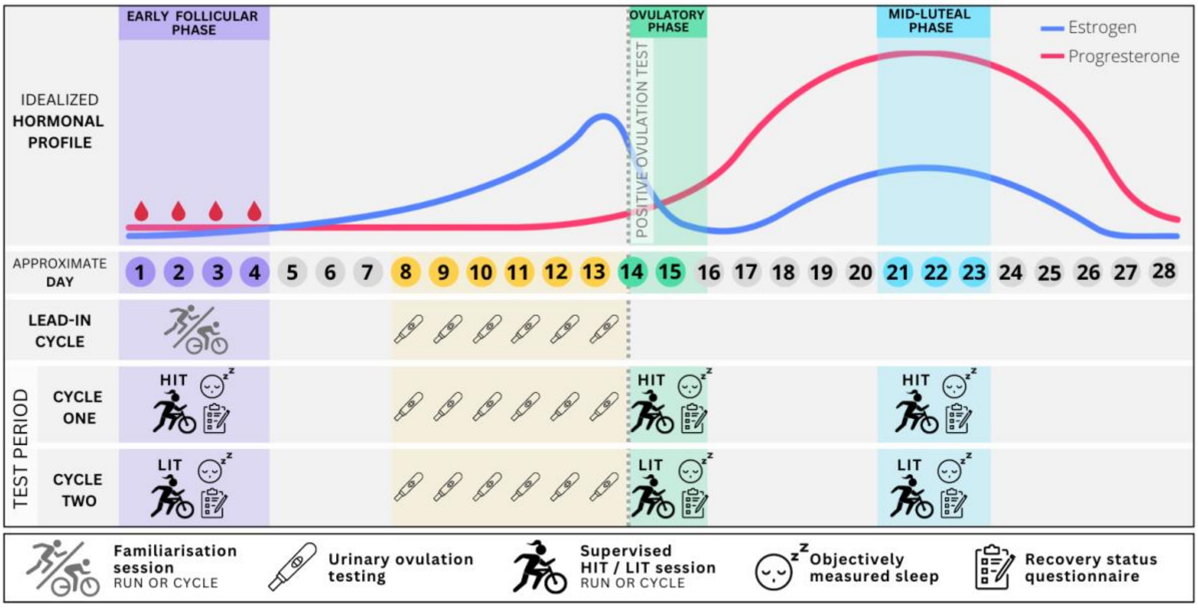


**Figure 2.** Illustration of study design. LIT = low-intensity training, HIT = high-intensity training.

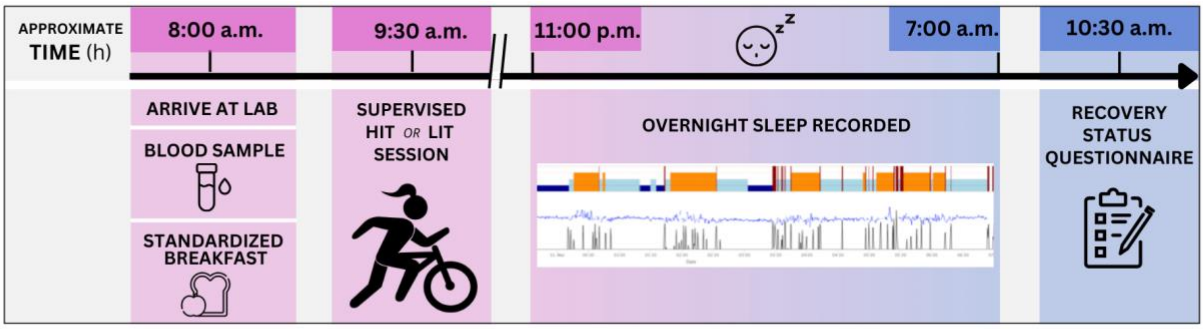


**Figure 3.** Illustration of test day protocols. LIT = low-intensity training, HIT = high-intensity training.

**MC phase determination.** MC phases were determined and verified using the three-step method [27], including calendar-based counting, detection of ovulation using a urinary ovulation kit (Clearblue Digital Ovulation Test, SPD Swiss Precision Diagnostics GmbH, Geneva, Switzerland), and serum hormone sampling on each test day.

Menstrual disturbances were defined as: a) oligomenorrhea, i.e., MC length >35 days and <90 days; b) anovulation, i.e., no ovulation detected by the urinary ovulation test; and c) luteal phase deficiency, i.e., progesterone concentration below 16 $nmol \cdot L^{-1}$ in the MLP.[21] Participants presenting with repeated anovulatory cycles during the lead-in period did not progress to the test period. MCs identified with a menstrual disturbance during the test period were retrospectively excluded from the analysis.

**Familiarization session**. During the EFP of the lead-in cycle participants completed a maximal incremental test to exhaustion in the laboratory either while running on a treadmill (Woodway PPS Med 55, Waukesha, Wisconsin, USA) or cycling on a cycle ergometer (Lode Sport Excalibur, Groningen, Netherlands). The running protocol started at 6.0 $km \cdot h^{-1}$ and an incline of 5%, with speed increments of 1 $km \cdot h^{-1}$ each minute until exhaustion. The cycling protocol started at 150 W and increased by 20 W each minute until exhaustion. The average intensity (velocity or power output) during the final minute of the incremental test ($iVO_{2peak}$) was used to calculate individualized exercise intensities for HIT and LIT. $VO_{2peak}$ was defined as the highest average 30-s $VO_2$ measurement using a moving average filter.

**Test day.** Participants were instructed to avoid HIT and consume an individualized high-carbohydrate diet consisting of 8 gram of carbohydrate per kg body weight[28] during the 24 h preceding each test. On each test day, participants arrived at the laboratory between 6:00 – 10:00 a.m. in a fasted state. A venous blood sample was drawn, and participants were provided with a standardized breakfast (2 g carbohydrate per kg body mass).

HIT started with a 15-min incremental warm up (3-min at 35%, 5-min at 45%, 5-min at 60%, 2-min at 40% of $iVO_{2peak}$) followed by five high-intensity interval blocks (4-min at 80% $iVO_{2peak}$ and 2-min at 40% $iVO_{2peak}$) and concluded with a 10-min cool down (5-min at 60%, 5-min at 35% of $iVO_{2peak}$). LIT started with a 13-min incremental warm up (3-min at 35%, 5-min at 45%, 5-min at 60% of $iVO_{2peak}$), followed by three low-intensity running blocks (3-min at 50% of $iVO_{2peak}$, 3-min at 45% $iVO_{2peak}$ and 7-min at 55% of $iVO_{2peak}$), or five low intensity cycling blocks (3-min at 50% of $iVO_{2peak}$ 3-min at 45% $iVO_{2peak}$ and 8-min at 55% of $iVO_{2peak}$) and concluded with an 8-min cool down (5-min at 60%, 3-min at 35% of $iVO_{2peak}$). Sessions were modeled from typical LIT and HIT sessions used in sport practice.[29]

Following the training session participants were instructed to avoid further training and/or specific recovery strategies (i.e., stretching, massage, etc.) for the subsequent 24 h.

**Sleep monitoring.** Overnight sleep was recorded with a Somnofy sleep monitor on the evening of each test day. Somnofy is a non-contact sleep monitor based on impulse radio ultra-wideband (IR-UWB) radar. It has previously been validated against polysomnography and showed substantial agreement (Cohen's kappa coefficient of 0.63) in detecting sleep/wake and sleep stages in healthy adults [30]. Variables investigated in the current study are described in Table 1.

**Table 1.** Description of sleep variables collected with the Somnofy sleep monitor

| SLEEP VARIABLE | UNIT | DESCRIPTION |
|---|---|---|
| **Sleep / wake variables** | | |
| Sleep onset latency | h | Time from lights off to sleep onset in any sleep stage |
| Total sleep time | h | Total sleep time achieved during the night |
| Wake after sleep onset | h | Time spent awake during the night |
| **Sleep stages** | | |
| Light sleep | % | Percentage of total sleep time in light stages of sleep |
| Deep sleep | % | Percentage of total sleep time in deep stages of sleep |
| Rapid eye movement sleep | % | Percentage of total sleep time in REM sleep |
| **Sleep quality** | | |
| Sleep efficiency | % | The percentage of time from sleep onset to wake-up that was spent asleep |

*Note*. Sleep stages are analyzed as percentages in order to account for the influence of total sleep time on the time spent in the different stages of sleep.

**Recovery Status Questionnaire.** 24 h after each training session participants completed a recovery status questionnaire, composed of The Perceived Recovery Status Scale[31] and the Hooper Scale[32] in the participants' native language (English or Norwegian). The former is a single-item questionnaire recording perceived recovery status on a scale of 0 (very poorly recovered / extremely tired) to 10 (very well recovered / highly energetic), validated for assessment of perceived next-day recovery following exercise.[31] The latter consisted of four items (sleep quality, fatigue, stress, and muscle soreness) ranked on a scale of 0 (very poor) to 7 (very good), which has been shown to be a stable and reliable tool to monitor fatigue and training load in athletes.[33,34]

**Blood sampling procedures and analysis.** A venous blood sample was drawn from an antecubital venipuncture on the morning of each test day. The sample was left to clot for 30-min, centrifuged and the serum was separated and stored at –80°C until analysis. The samples were analyzed for estradiol, progesterone, follicle–stimulating hormone and luteinizing hormone using liquid chromatography-tandem mass spectrometry at the University Hospital of Northern Norway, Tromsø, Norway (ISO/IEC 15189).

**Data compliance**. Each of the 15 participants attended up to 6 test days, one in each of the three MC phases following a LIT and a HIT training session, respectively. From the 90 possible test days, 27 days (30%) were retrospectively excluded (see Figure 1 for details), resulting in a total of 63 days included in the final analysis. Overall compliance for nights of recorded sleep and response to individual items on the recovery status questionnaire was 81% and 89%, respectively. Missing data was assumed to occur at random.

**Equity, diversity and inclusion statement.** Only biological females were included in this study. Women from diverse cultural and socioeconomic backgrounds were welcome to participate. Authors from a variety of career stages were included, of which the first and last authors are women.

**Statistical Analysis.** Data were analyzed using linear mixed effects regression models. The association between the dependent (sleep/recovery) and independent variables (MC phase/session type) were modeled with a random intercept for participant and MC phase nested within participant. Models included MC phase (levels: EFP; OP; MLP), session type (levels: LIT; HIT), and their interaction (MC phase by session type) as fixed factors. The alpha level was set at 0.05. Significant main effects were investigated using pairwise comparisons with a Tukey correction. Unless otherwise stated, results are presented as estimated marginal means with 95% confidence intervals (CI), followed by p-values. Effect sizes were estimated using marginal $R^2$ (i.e., effects explained by fixed factors; $mR^2$) and Cohen's *d*.[35] The sigma used for calculating Cohen's *d* was the square root of pooled random variance. Cohen's *d* values were interpreted as; small (*d*=0.20-0.49), medium (*d*=0.50-0.79), and large (*d*≥0.80).[36] For analyses with singular fit (light sleep and sleep efficiency), Cohen's *d* was not reported.

All statistical analyses were performed using R in RStudio,[37] with the packages "lme4" (version 1.1-29), "emmeans" (version 1.8.4-1) and "ggplot2" (version 3.3.6), "JWileymisc" (version 1.4.1).

# RESULTS

## Menstrual Cycle Characteristics

Menstrual disturbances were observed in 26% of the recorded MCs (Figure 1). Thus, 26 eumenorrheic MCs with 63 phase-specific test days were included in the analysis (EFP=21, OP=19, MLP=23). MC length ranged from 25–33 days (mean±SD: 28±2) and the day of ovulation ranged from day 9–21 (mean±SD: 14±3). Serum hormone concentrations were reflective of eumenorrheic MCs and are presented in Table 2.

**Table 2.** Serum concentrations of ovarian hormones in three phases of the menstrual cycle

| HORMONE | EFP | OP | MLP |
|---|---|---|---|
| Estradiol (pmol·L$^{-1}$) | 127 (92–176) | 365 (251–510) | 544 (610–677) |
| Progesterone (nmol·L$^{-1}$) | 0.4 (0.3–0.7) | 3.6 (2.5–9.6) | 41.8 (28.8–51.5) |
| Luteinizing Hormone (IU·L$^{-1}$) | 5.9 (5.2–7.1) | 15.4 (8.9–17.6) | 7.1 (3.6–10.0) |
| Follicle Stimulating Hormone (IU·L$^{-1}$) | 5.7 (4.2–6.8) | 6.2 (5.6–7.9) | 3.4 (2.3–4.2) |

Values are presented as median and interquartile ranges.
EFP: Early follicular phase; OP: Ovulatory phase; MLP: Mid-luteal phase.

**MC Phase.** A main effect of MC phase on wake after sleep onset (p<.001, $mR^2$=19%) was observed. In MLP, wake after sleep onset was 34 min (95% CI: 26 min, 43 min), representing a 12 min (95% CI: 24 min, 0.3 min) increase from EFP (p=0.043, *d*=0.3) and a 19 min (95% CI: 31 min, 7 min) increase from OP (p=0.001, *d*=0.5). There was a main effect of MC phase on light sleep (p=0.023, $mR^2$=13%). Light sleep was 54.1% (95% CI: 51.2%, 57.0%) in EFP, and increased by 5.1% (95% CI: 10.0%, 0.3%) in MLP (p=0.037).

There was a main effect of MC phase on deep sleep (p=0.045, $mR^2$=8%), although no significant differences were found in pairwise comparisons. Lastly, there was a main effect of MC phase on sleep efficiency (p=0.033, $mR^2$=7%). Sleep efficiency was 90.1% (95% CI: 86.8%, 93.3%) in OP and decreased by 3.5% (95% CI: 2.4%, 0.1%) in MLP (p=0.047). Total sleep time remained stable across MC phases (p=0.966), with an average duration of 7.6 (95% CI: 7.4 hours, 7.8 hours). MC phase had no significant effect on any of the recovery status questionnaire variables.

**Session Type.** A main effect of session type (HIT/LIT) on perceived recovery (p<.001, $mR^2$=34%) and perceived muscle soreness (p=0.007, $mR^2$=15.0%) was observed. Perceived recovery was 7.8 points (95% CI: 7.2 points, 8.3 points) following LIT and 1.3 points (95% CI: 0.6 points, 1.9 points) lower following HIT (p<.001, d=-1.0). Perceived muscle soreness was 5.8 points (95% CI: 5.3 points, 6.2 points) following LIT, and 0.8 points (95% CI: 0.1 points, 1.4 points) higher following HIT (p=0.018, d=0.6). There were no significant effects of session type on any of the objective sleep variables, perceived-sleep quality, -fatigue or -stress.

No interactions between MC phase and session type were observed for any of the reported variables. Individual data points and group means are presented by main effect in Figure 4. Figures of the interaction models can be found in the supplementary materials.

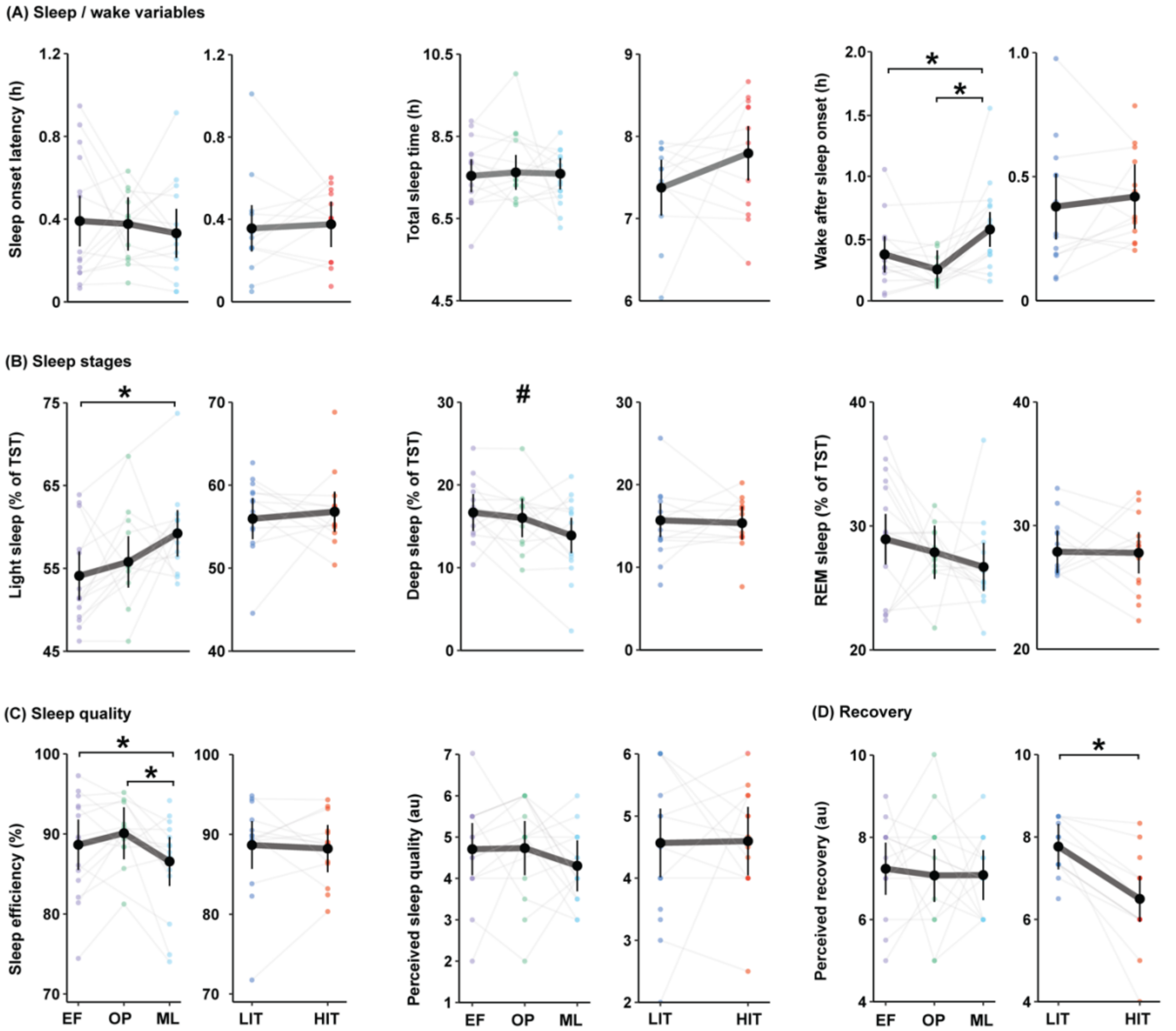


**Figure 4.** The effect of menstrual cycle (MC) phase and exercise intensity on (A) sleep/wake variables, (B) sleep stages, (C) sleep quality, and (D) perceived recovery. Data represents objective sleep and perceived recovery data of 15 endurance-trained females in early follicular phase (EFP, in purple), ovulatory phase (OP, in green) and mid-luteal phase (MLP, in light blue dots); and following standardized low-intensity training (LIT, indark blue) and high-intensity training (HIT, in red) sessions. Black dots connected by grey thick lines represent the estimated marginal means, error bars indicate 95% confidence intervals. Individual data points are connected by a thin line. Brackets annotated with * denote a significant difference between given pairs, and # denotes a significant main effect of MC phase.

## DISCUSSION

This study investigated the influence of MC phase on objectively measured sleep and perceived recovery status following two commonly practiced session types (HIT and LIT) in endurance-trained women. The main findings were; 1) sleep was impaired following exercise in MLP, indicated by more time awake after sleep onset in MLP compared to EFP and OP, lower sleep efficiency in MLP compared to EFP and a greater proportion of light sleep in MLP compared to OP, 2) none of the perceived recovery status items were influenced by MC phase, but perceived recovery was impaired following HIT compared to LIT along with more perceived muscle soreness, and 3) the effects of MC phase on sleep and recovery was not modulated by session type.

The findings that MC phase affected the objective characteristics of sleep are consistent with previous studies in non-athletic groups which have shown similar patterns of more time awake after sleep onset, lower sleep efficiency and more light sleep in the luteal phase compared to the follicular phase.[10,12,13,38,39] During the luteal phase, the rise in progesterone triggers an increase in core body temperature which has direct and indirect effects on the regulation of sleep.[40] For instance, elevated core body temperature in the luteal phase has been linked to increased sleep fragmentation,[40] which may be further exaggerated by steeper increases in progesterone from the follicular to the luteal phase.[41] Additionally, estrogen and progesterone receptors are localized in many sleep-regulatory centers in the brain which directly influence multiple aspects of the sleep/wake cycle.[13,42] In the current study, the most pronounced phase-based sleep disruption was attributed to increases in wake after sleep onset from EFP (22 min) and OP (15 min) to MLP (34 min). The variation between EFP and MLP is consistent with what has been found in untrained populations (~ +40%).[10,43] While mid-sleep awakenings are a normal part of the sleep cycle, more than 20 min awake after sleep onset is indicative of impaired sleep quality.[44] Beyond this finding, the other objective sleep variables (i.e. total sleep time, sleep efficiency, sleep stages) remained within the recommendations for “good sleep quality”[44] across the recorded phases. Particularly when compared to patients with sleep/wake disorders[45] or even in athletes as a result of early-morning training sessions,[46] the magnitude of the sleep alterations between MC phases were quite modest. Thus, it remains unclear if these sleep alterations would affect performance and/or long-term athletic development.

The results of the current study contradict Hrozanova et al.,[7] who reported reduced sleep efficiency during the follicular phase compared to the luteal phase, along with more time in bed and less light sleep during the bleeding compared to non-bleeding days in a group of junior endurance athletes. They proposed that the sleep impairments could be related to a higher prevalence of MC symptoms during the bleeding days of the cycle. Indeed, MC symptoms such as abdominal cramping, headaches and stress have been shown to negatively affect percieved sleep quality,[47] however associations with objective sleep variables have not been established.[10] It is likley that the relationship between MC symptoms and sleep is independent of MC phase, since various symptom patterns are possible within a group of individuals.[47] That is to say, experiencing abdominal cramping would reduce percieved sleep quality regardless of when during the MC these symptoms occur. Thus, further research is certainly required in this area. Finally, the aformentioned study[7] used calendar-based counting to establish MC phases, which introduces some uncertainty into the phase-based comparisons since neither ovulation nor hormonal concentrations were confirmed.[21] Since exercising women have a high prevelance of subtle menstrual disturbances (i.e. annovulation) [48], and thus abnormal hormonal profiles, it is difficult to compare findings across studies.

Despite the observed changes in the objective sleep variables, perceived sleep quality and the other perceived recovery parameters did not differ between MC phases in the current study. The mismatch between objective and perceived sleep quality outcomes is well documented in the literature,[11,43,49] and may be attributed to the way perceived sleep is conceptualized. As such, an individual's perceived sleep quality rating is likely to reflect elements related to sleep and non-sleep phenomena (i.e. stress, mood or pain). Likewise, individuals reporting on perceived sleep quality ratings may disproportionately emphasize specific aspects of their sleep (i.e. inability to fall asleep versus time spent awake).[49] To date, there is little consistency in the literature regarding the effect of the MC on perceived sleep quality. Studies in untrained women have reported lower subjective sleep quality preceding menstruation, during menstruation and mid-cycle,[9,47] or no effect,[11] while a study in trained women showed a small reduction in perceived sleep quality during the MLP compared to other phases.[16] The discrepancy across studies could be a result of different methodological approaches such as the timepoints when data was collected, verification of MC phase and participant group characteristics. Nevertheless, perceived sleep quality has been associated with changes in stress, fatigue, perceived recovery and mood in athletic groups,[50,51] and remains a distinct and valuable indicator of sleep and recovery for athletic monitoring.

No changes in perceived-sleep quality, fatigue or stress following either session type (HIT/LIT) were observed in the current study, however, participants reported feeling less recovered, and having more perceived muscle soreness following HIT sessions compared to LIT sessions. The influence of HIT on recovery status could be mediated by the effect of HIT on exercise-induced muscle damage.[52] Session type did not influence any of the objectively measured sleep parameters or perceived sleep quality. While physical activity is generally considered to be beneficial to sleep, the relationship is moderated by factors such as sex, fitness level and the characteristics and timing of exercise.[24] The participants in the current group were regularly performing HIT sessions prior to the study period and the training session was always performed in the morning, so possibly the stimulus was not strong enough to induce changes in sleep quality. Interestingly, no interaction effects were found for MC phase and session type. Thus, it appears that session type does not specifically influence the potential for recovery following exercise in the different phases of the MC, rather both exert independent effects on the assessed variables.

## Strengths and Limitations

This study utilized gold standard methodology to determine and verify MC phases.[27] This led to the identification and exclusion of multiple abnormal MCs (~25%) which would otherwise be included if simpler MC phase verification methods were used. Women presenting with menstrual disorders are more likely to suffer from sleep disturbances,[12] so the use of high quality methodology is especially important when undertaking such studies. Additionally, the participant group was well-trained, and HIT and LIT sessions are widely used for training purposes in a variety of endurance sports, making the outcomes of this study practically relevant.

We acknowledge that the study also has some limitations. The current study design focused only on three pre-defined phases of the MC. This design does not account for the broader changes that may occur throughout the MC. Furthermore, we defined perceived sleep quality based on a single item response, which cannot discretely reflect the nuances of sleep quality, such as difficulty falling asleep versus difficulty staying asleep. However, this is a commonly used metric in sleep and training diaries, and has been shown to correlate well with multiple indices of objective sleep[49] and recovery status[50]. Lastly, the sample size was low, and may not have sufficient statistical power to identify small between-phase differences, such as the effect of MC phase on deep sleep.

## PRACTICAL APPLICATIONS

Short-term consequences of reduced sleep quality include increased stress, mood disturbances and daytime exhaustion.[53,54] Thus, while minor, the observed impairments to sleep in the MLP may warrant additional considerations around sleep hygiene and behaviors during the latter half of the MC. For instance, avoiding caffeine intake within 9 hours of scheduled bedtime, reducing evening screentime and keeping the bedroom cool have all been shown to positively influence sleep quality.[55] Concurrently, recovery times following HIT sessions may be adjusted to accommodate deviations in perceived recovery and muscle soreness, possibly preventing accumulation of fatigue [3]. In a research setting, researchers should consider if and how MC-related changes in sleep may influence their study design and outcomes. Future studies should consider including measurements in the late luteal phase as well as objective and subjective sleep measurements over several days within each phase to further uncover the nuances of how the MC influences sleep quality in exercising women.

## CONCLUSION

The current study revealed an effect of MC phase on objectively measured sleep, with indications of impaired sleep in the MLP. However, the magnitude of the sleep alterations was modest, and so it remains unclear if these changes would practically influence training adaptations and/or performance. Perceived recovery was influenced by session type but not MC phase, suggesting that athletes and coaches can schedule training sessions without concern for MC phase-related variations in perceived recovery, and rather plan according to logistical convenience. Additional research should investigate if sleep and perceived recovery measures also follow similar pattens in athletes with abnormal MCs, or in those using hormonal contraceptives.

**Competing interests.** None to declare.

**Acknowledgements.** This study was a work package of the FENDURA project at UiT The Arctic University of Norway, in collaboration with the Norwegian University of Science and Technology (NTNU), the Norwegian School of Sports Sciences (NIH), the Norwegian Olympic Committee (Olympiatoppen), the Norwegian Ski Federation, and the Norwegian Biathlon Federation. The authors thank Thomas Haugen, Boye Welde, Bente Morseth, Klavs Madsen and Guro S. Solli, for their contributions, the University Hospital of Northern Norway for their support analyzing blood samples (Guri Grimnes, Ole Martin Fuskevåg, Silja Breivik), the laboratory technicians for their assistance during the study period (Hege Nymo Østgaard, Anna Lena Muller, Gina F. Øistuen and Vilde Sophie Sogn) and the participants for their enthusiasm, and commitment to this study.

This study was funded by the Tromsø Research Foundation (Project-ID: 19_FENDURA_BW) and UiT The Arctic University of Norway. The submission and page charges for this article have been funded by a grant from the publication fund of UiT The Arctic University of Norway.

## REFERENCES

1. Ansdell P, Thomas K, Hicks KM, Hunter SK, Howatson G, Goodall S. Physiological sex differences affect the integrative response to exercise: acute and chronic implications. *Experimental Physiology*. 2020;105(12):2007-2021. doi:https://doi.org/10.1113/EP088548
2. Vogel K, Larsen B, McLellan C, Bird SP. Female athletes and the menstrual cycle in team sports: current state of play and considerations for future research. *Sports*. 2024;12(1):4.
3. Kellmann M, Bertollo M, Bosquet L, et al. Recovery and performance in sport: consensus statement. *International Journal Sports Physiology and Performance*. 2018;13(2):240-245. doi:10.1123/ijspp.2017-0759
4. Selmi O, Ouergui I, Muscella A, et al. Monitoring psychometric states of recovery to improve performance in soccer players: a brief review. *International Journal of Environmental Research and Public Health*. 2022;19doi:10.3390/ijerph19159385
5. Cowley ES, Olenick AA, McNulty KL, Ross EZ. “Invisible Sportswomen”: The sex data gap in sport and exercise science research. *Women in Sport and Physical Activity Journal*. 2021;29(2):146-151. doi:10.1123/wspaj.2021-0028
6. Power CJ, Fox JL, Elliott-Sale KJ, Bender AM, Dalbo VJ, Scanlan AT. Waking up to the issue! Research inattention and sex-related differences warrant more sleep studies in female athletes. *Sports Medicine*. 2023;doi:10.1007/s40279-023-01963-5
7. Hrozanova M, Klöckner CA, Sandbakk Ø, Pallesen S, Moen F. Sex differences in sleep and influence of the menstrual cycle on women’s sleep in junior endurance athletes. *PloS one*. 2021;16(6):e0253376. doi:10.1371/journal.pone.0253376
8. Carmichael MA, Thomson RL, Moran LJ, et al. A pilot study on the impact of menstrual cycle phase on elite australian football athletes. *International Journal of Environmental Research and Public Health*. 2021;18(18)doi:10.3390/ijerph18189591
9. Baker FC, Driver HS. Self-reported sleep across the menstrual cycle in young, healthy women. *Journal of Psychosomatic Research*. 2004;56(2):239-243. doi:https://doi.org/10.1016/S0022-3999(03)00067-9
10. Baker FC, Kahan TL, Trinder J, Colrain IM. Sleep quality and the sleep electroencephalogram in women with severe premenstrual syndrome. *Sleep*. 2007;30(10):1283-91. doi:10.1093/sleep/30.10.1283
11. Li DX, Romans S, De Souza MJ, Murray B, Einstein G. Actigraphic and self-reported sleep quality in women: associations with ovarian hormones and mood. *Sleep Medicine*. 2015;16(10):1217-1224. doi:https://doi.org/10.1016/j.sleep.2015.06.009
12. Baker FC, Lee KA. Menstrual cycle effects on sleep. *Sleep Medicine Clinical*. 2022;17(2):283-294. doi:10.1016/j.jsmc.2022.02.004

13. Dorsey A, de Lecea L, Jennings KJ. Neurobiological and hormonal mechanisms regulating women's sleep. *Frontiers Neuroscience*. 2020;14:625397. doi:10.3389/fnins.2020.625397
14. Siegel JM. Clues to the functions of mammalian sleep. *Nature*. 2005;437(7063):1264-71. doi:10.1038/nature04285
15. Walsh NP, Halson SL, Sargent C, et al. Sleep and the athlete: narrative review and 2021 expert consensus recommendations. *British Journal of Sports Medicine*. 2020;doi:10.1136/bjsports-2020-102025
16. De Martin Topranin V, Engseth TP, Hrozanova M, Taylor M, Sandbakk Ø, Noordhof DA. The influence of menstrual-cycle phase on measures of recovery status in endurance athletes: The Female Endurance Athlete Project. *International journal of sports physiology and performance*. 2023:1-8. doi:10.1123/ijspp.2022-0325
17. Sims ST, Ware L, Capodilupo ER. Patterns of endogenous and exogenous ovarian hormone modulation on recovery metrics across the menstrual cycle. *BMJ Open Sport Exercise Medicine*. 2021;7(3):e001047. doi:10.1136/bmjsem-2021-001047
18. Cook CJ, Kilduff LP, Crewther BT. Basal and stress-induced salivary testosterone variation across the menstrual cycle and linkage to motivation and muscle power. *Scandinavian journal of medicine & science in sports*. 2018;28:1345 - 1353.
19. Driver HS, Dijk DJ, Werth E, Biedermann K, Borbély AA. Sleep and the sleep electroencephalogram across the menstrual cycle in young healthy women. *Journal of Clinical Endocrinology and Metabolism*. 1996;81(2):728-35. doi:10.1210/jcem.81.2.8636295
20. Hackney AC, Kallman AL, Ağgön E. Female sex hormones and the recovery from exercise: Menstrual cycle phase affects responses. *Biomedical Human Kinetics*. 2019;11(1):87-89. doi:10.2478/bhk-2019-0011
21. Elliott-Sale KJ, Minahan CL, de Jonge XAKJ, et al. Methodological considerations for studies in sport and exercise science with women as participants: A working guide for standards of practice for research on women. *Sports Medicine*. 2021;doi:10.1007/s40279-021-01435-8
22. Sims ST, Heather AK. Myths and methodologies: Reducing scientific design ambiguity in studies comparing sexes and/or menstrual cycle phases. *Experimental Physiology*. 2018;103(10):1309-1317. doi:10.1113/ep086797
23. McNulty KL, Elliott-Sale KJ, Dolan E, et al. The effects of menstrual cycle phase on exercise performance in eumenorrheic women: A systematic review and meta-analysis. *Sports Medicine*. 2020;doi:10.1007/s40279-020-01319-3
24. Aloulou A, Duforez F, Léger D, De Larochelambert Q, Nedelec M. The relationships between training load, type of sport, and sleep among high-level adolescent athletes. *International Journal of Sport Physiology and Performance*. Jun 1 2021;16(6):890-899. doi:10.1123/ijspp.2020-0463
25. Hrozanova M, Klöckner CA, Sandbakk Ø, Pallesen S, Moen F. Reciprocal associations between sleep, mental strain, and training load in junior endurance athletes and the role of poor subjective sleep quality. *Frontiers Psychology*. 2020;11:545581. doi:10.3389/fpsyg.2020.545581
26. McKay AKA, Stellingwerff T, Smith ES, et al. Defining training and performance caliber: A participant classification framework. *International Journal of Sport Physiology and Performance*. 2022;17(2):317-331. doi:10.1123/ijspp.2021-0451
27. Schaumberg MA, Jenkins DG, Janse de Jonge XAK, Emmerton LM, Skinner TL. Three-step method for menstrual and oral contraceptive cycle verification. *Journal of Science and Medicine in Sport*. 2017;20(11):965-969. doi:10.1016/j.jsams.2016.08.013

28. Thomas DT, Erdman KA, Burke LM. American College of Sports Medicine joint position statement. Nutrition and athletic performance. *Medicine and science in sports and exercise*. 2016;48(3):543-68. doi:10.1249/mss.0000000000000852
29. Sandbakk Ø, Haugen T, Ettema G. The influence of exercise modality on training load management. *International Journal of Sport Physiology and Performance*. 2021;16(4):605-608. doi:10.1123/ijspp.2021-0022
30. Toften S, Pallesen S, Hrozanova M, Moen F, Grønli J. Validation of sleep stage classification using non-contact radar technology and machine learning (Somnofy®). *Sleep Medicine*. 2020;75:54-61. doi:10.1016/j.sleep.2020.02.022
31. Laurent M, Green J, Bishop P, et al. A practical approach to monitoring recovery: development of a perceived recovery status scale. *Journal of Strength and Conditioning Research* 2011;25:620-8. doi:10.1519/JSC.0b013e3181c69ec6
32. Hooper SL, Mackinnon LT. Monitoring overtraining in athletes. Recommendations. *Sports Medicine*. 1995;20(5):321-7. doi:10.2165/00007256-199520050-00003
33. Moalla W, Fessi MS, Farhat F, Nouira S, Wong DP, Dupont G. Relationship between daily training load and psychometric status of professional soccer players. *Research in Sports Medicine*. 2016;24(4):387-394. doi:10.1080/15438627.2016.1239579
34. Rabbani A, Clemente FM, Kargarfard M, Chamari K. Match fatigue time-course assessment over four days: Usefulness of the hooper index and heart rate variability in professional soccer players. Original Research. *Frontiers in Physiology*. 2019;10doi:10.3389/fphys.2019.00109
35. Nakagawa S, Schielzeth H. A general and simple method for obtaining R2 from generalized linear mixed-effects models. *Methods in Ecology and Evolution*. 2013;4(2):133-142. doi:https://doi.org/10.1111/j.2041-210x.2012.00261.x
36. Cohen J. *Statistical Power Analysis for the Behavioral Sciences*. Routledge; 1988.
37. *R: A language and environment for statistical computing*. R Foundation for Statistical Computing; 2021. https://www.R-project.org/
38. Baker FC, Driver HS, Paiker J, Rogers GG, Mitchell D. Acetaminophen does not affect 24-h body temperature or sleep in the luteal phase of the menstrual cycle. *Journal of Applied Physiology*. 2002;92(4):1684-1691. doi:10.1152/japplphysiol.00919.2001
39. Manber R, Bootzin R. Sleep and the menstrual cycle. *Health Psychology*. 1997;16:209-214. doi:10.1037/0278-6133.16.3.209
40. Baker FC, Siboza F, Fuller A. Temperature regulation in women: Effects of the menstrual cycle. *Temperature (Austin)*. 2020;7(3):226-262. doi:10.1080/23328940.2020.1735927
41. Sharkey KM, Crawford SL, Kim S, Joffe H. Objective sleep interruption and reproductive hormone dynamics in the menstrual cycle. *Sleep Med*. 2014;15(6):688-93. doi:10.1016/j.sleep.2014.02.003
42. Mong JA, Baker FC, Mahoney MM, et al. Sleep, rhythms, and the endocrine brain: influence of sex and gonadal hormones. *Journal of Neuroscience*. 2011;31(45):16107-16. doi:10.1523/jneurosci.4175-11.2011
43. Shechter A, Varin F, Boivin DB. Circadian variation of sleep during the follicular and luteal phases of the menstrual cycle. *Sleep*. 2010;33(5):647-56. doi:10.1093/sleep/33.5.647
44. Ohayon M, Wickwire EM, Hirshkowitz M, et al. National Sleep Foundation's sleep quality recommendations: first report. *Sleep Health*. 2017;3(1):6-19. doi:https://doi.org/10.1016/j.sleh.2016.11.006

45. Baglioni C, Nanovska S, Regen W, et al. Sleep and mental disorders: A meta-analysis of polysomnographic research. *Psychological Bulletin*. 2016;142(9):969-990. doi:10.1037/bul0000053

46. Sargent C, Halson S, Roach GD. Sleep or swim? Early-morning training severely restricts the amount of sleep obtained by elite swimmers. *European Journal Sport Science*. 2014;14 Suppl 1:S310-5. doi:10.1080/17461391.2012.696711

47. Van Reen E, Kiesner J. Individual differences in self-reported difficulty sleeping across the menstrual cycle. *Archives of Womens Mental Health*. 2016;19(4):599-608. doi:10.1007/s00737-016-0621-9

48. De Souza MJ, Toombs RJ, Scheid JL, et al. High prevalence of subtle and severe menstrual disturbances in exercising women: confirmation using daily hormone measures. *Human Reproduction*. 2010;25(2):491-503. doi:10.1093/humrep/dep411

49. Krystal AD, Edinger JD. Measuring sleep quality. *Sleep Medicine*. 2008;9:S10-S17. doi:https://doi.org/10.1016/S1389-9457(08)70011-X

50. Sawczuk T, Jones B, Scantlebury S, Till K. Influence of perceptions of sleep on well-being in youth athletes. *The Journal of Strength & Conditioning Research*. 2021;35(4):1066-1073. doi:10.1519/jsc.0000000000002857

51. Hamlin MJ, Deuchrass RW, Olsen PD, et al. The effect of sleep quality and quantity on athlete's health and perceived training quality. *Frontiers in Sports and Active Living*. 2021;3:705650. doi:10.3389/fspor.2021.705650

52. Leite CDFC, Zovico PVC, Rica RL, et al. Exercise-induced muscle damage after a high-intensity interval exercise session: systematic review. *International Journal Environmental Research Public Health*. 2023;20(22)doi:10.3390/ijerph20227082

53. Medic G, Wille M, Hemels ME. Short- and long-term health consequences of sleep disruption. *Natural Science of Sleep*. 2017;9:151-161. doi:10.2147/nss.S134864

54. Nelson KL, Davis JE, Corbett CF. Sleep quality: An evolutionary concept analysis. *Nursing Forum*. 2022;57(1):144-151. doi:https://doi.org/10.1111/nuf.12659

55. Vitale KC, Owens R, Hopkins SR, Malhotra A. Sleep hygiene for optimizing recovery in athletes: review and recommendations. *International Journal of Sports Medicine*. 2019;40(8):535-543. doi:10.1055/a-0905-3103