Original Article

PHYSIOLOGICAL AND AUTONOMIC RESPONSES ACROSS MENSTRUAL PHASES IN THAI FEMALE ATHLETES: EVIDENCE FROM THAILAND NATIONAL SPORTS UNIVERSITY, CHIANG MAI CAMPUS AND CHANDRAKASEM RAJABHAT UNIVERSITY

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ABSTRACT

This study investigated physiological, hormonal, and psychosocial dynamics of female athletes, aiming to advance integrative approaches beyond menstrual cycle perspectives. A mixed-methods design included 60 athletes from two Thai universities, monitored over two cycles. Quantitative assessments comprised maximum oxygen uptake (VO_{2max}) lactate threshold, heart rate variability (HRV), core temperature, gastrocnemius contractility, body composition, and energy availability, supported by wearable monitoring. Menstrual phases were verified through basal body temperature and self-reported symptoms. Qualitative data were obtained from interviews and focus groups. Results showed VO_{2max} and lactate threshold were stable across phases, while HRV declined and core temperature increased in the luteal phase. About 20% of athletes were at risk of Relative Energy Deficiency in Sport (RED-S), linked to reduced HRV, higher exertion, and greater injury incidence. Thematic analysis identified four themes: perceived menstrual impact, adaptive self-monitoring, psychosocial barriers, and value of technology in training. Findings suggest that while physical performance remains stable, recovery capacity, injury risk, and subjective perceptions of female athlete are predominantly influenced by hormonal factors. Practical implications include cycle monitoring, RED-S screening, wearable-based load management, and culturally responsive coach education. Integrating physiological, technological, and psychosocial approaches can enhance female athlete health and performance in Thailand and globally.

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นิพนธ์ต้นฉบับ

การตอบสนองทางสรีรวิทยาและระบบประสาทอัตโนมัติในช่วงรอบประจำเดือนของนักกีฬาหญิงไทย: หลักฐานจากมหาวิทยาลัยการกีฬาแห่งชาติ วิทยาเขตเชียงใหม่ และมหาวิทยาลัยราชภัฏจันทรเกษม

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บทคัดย่อ

การศึกษานี้ตรวจสอบพลวัตด้านสรีรวิทยา ฮอร์โมน และจิตสังคมของนักกีฬาหญิง โดยมีเป้าหมายเพื่อพัฒนาแนวทางบูรณาการที่ก้าวไกลเกินกว่ามุมมองรอบประจำเดือน ใช้ระเบียบวิธีแบบผสม โดยมีนักกีฬาหญิง 60 คนจากมหาวิทยาลัยไทย 2 แห่ง ติดตามผลตลอดรอบประจำเดือน 2 รอบเต็ม ข้อมูลเชิงปริมาณประกอบด้วย ความสามารถในการใช้ออกซิเจนสูงสุด ขีดจำกัดกรดแลคเตท ความแปรปรวนของอัตราการเต้นหัวใจ อุณหภูมิแกนกลาง ความหดตัวของกล้ามเนื้อน่อง องค์ประกอบร่างกาย และค่าพลังงานที่เพียงพอ พร้อมด้วยการติดตามด้วยอุปกรณ์สวมใส่ ระยะของรอบประจำเดือนถูกการตรวจสอบจากอุณหภูมิร่างกายขณะพักร่วมกับการรายงานอาการด้วยตนเอง ข้อมูลเชิงคุณภาพได้จากการสัมภาษณ์และการสนทนากลุ่ม ผลการวิจัยพบว่าปริมาณการใช้ออกซิเจนสูงสุด และขีดจำกัดกรดแลคเตทมีเสถียรภาพทุกช่วงรอบ แต่ความแปรปรวนของอัตราการเต้นหัวใจลดลงและอุณหภูมิแกนกลางสูงขึ้นในระยะลูเตียล ประมาณ 20% ของนักกีฬาอยู่ในกลุ่มเสี่ยงต่อภาวะร่างกายได้รับพลังงานและสารอาหารน้อยกว่าพลังงานที่ใช้ออกไป ซึ่งสัมพันธ์กับความแปรปรวนของอัตราการเต้นหัวใจที่ลดลง ค่าออกแรงที่สูงขึ้น และความเสี่ยงการบาดเจ็บที่มากขึ้น การวิเคราะห์เชิงคุณภาพพบ 4 ประเด็นหลัก ได้แก่ การรับรู้ผลกระทบของรอบเดือน การติดตามและปรับตัวด้วยตนเอง อุปสรรคทางจิตสังคม และคุณค่าของเทคโนโลยีในฝึกซ้อม ผลการวิจัยชี้ให้เห็นว่า แม้ว่าสมรรถภาพทางกายโดยรวมจะคงที่ แต่ความสามารถในการฟื้นตัว ความเสี่ยงต่อการบาดเจ็บ และการรับรู้เชิงอัตวิสัยวิสัยของนักกีฬาหญิงมีแนวโน้มได้รับอิทธิพลอย่างมากจากปัจจัยด้านฮอร์โมน ข้อเสนอเชิงปฏิบัติ ได้แก่ การติดตามรอบเดือน การคัดกรองภาวะร่างกายได้รับพลังงานและสารอาหารน้อยกว่าพลังงานที่ใช้ การจัดการภาระงานการฝึกด้วยอุปกรณ์สวมใส่ และการอบรมผู้ฝึกสอนที่ตอบสนองต่อบริบททางวัฒนธรรม การบูรณาการแนวทางด้านสรีรวิทยา เทคโนโลยี และจิตวิทยาสังคม สามารถเสริมสร้างสุขภาพและสมรรถภาพของนักกีฬาหญิงทั้งในประเทศไทยและในระดับสากล

(วารสารวิทยาศาสตร์และเทคโนโลยีการกีฬา 2568; 25(2): 17-32)

คำสำคัญ: เวชศาสตร์การกีฬา / วิทยาศาสตร์การกีฬา / รอบเดือน / ระบบพลังงาน / นักกีฬาหญิง

INTRODUCTION

For decades, sport science research has largely centered on male participants, leading to the widespread generalization of male-derived physiological models to female athletes despite clear biological distinctions. These include differences in hormonal regulation, energy metabolism, recovery mechanisms, and musculoskeletal function [1,2]. Recent years have seen an increasing recognition of the need for female-specific research that accounts for the complexity of menstrual cycle dynamics and their interaction with endocrine, nutritional, and environmental factors influencing both performance and well-being [3–5]. This shift reflects the emergence of precision sports science, emphasizing individualized, evidence-based monitoring to optimize performance and safeguard health—an area still underrepresented in Thai athletic contexts.

Initially, research on female athletes focused primarily on the menstrual cycle, attempting to identify predictable variations in performance across follicular, ovulatory, and luteal phases [4,5]. However, these early findings were often inconsistent, largely due to small sample sizes, inaccurate verification of cycle phases, and significant inter-individual variability [6]. Recent meta-analyses have confirmed that although menstrual phase effects may exist, they are generally small and highly individualized, underscoring the importance of personalized monitoring rather than the application of generalized assumptions [4]. Moreover, methodological advancements, including biomarker verification of menstrual phases and longitudinal designs, have improved the rigor and reproducibility of research in this area [1,6]. As a result, female physiology is increasingly recognized as a distinct and legitimate focus within sport science rather than an extension of male-centric models.

Beyond the menstrual cycle, it has become clear that female performance is influenced by multiple hormonal factors throughout the lifespan. Hormonal contraceptives, for example, alter endogenous estrogen and progesterone levels, potentially affecting thermoregulation, substrate utilization, and muscle recovery [3,8]. Similarly, peri- and postmenopausal women experience declining sex hormone concentrations, which may influence bone density, cardiovascular function, and muscular adaptation [9]. Additionally, insufficient energy availability, often manifesting as Relative Energy Deficiency in Sport (RED-S), has been linked to menstrual irregularities, impaired bone health, and metabolic dysfunction [12]. Therefore, contemporary approaches to female athlete performance must integrate hormonal status with nutritional, environmental, and psychosocial factors, reflecting a more holistic perspective on health and performance.

Despite extensive research, the relationship between menstrual cycle phases and performance remains complex and sometimes contradictory. While some studies suggest minor decreases in performance during the early follicular phase, when both estrogen and progesterone are low, others report minimal differences across the cycle [4,6,7]. Importantly, psychosocial and cultural factors also influence athletes' perceptions of performance, with many female athletes perceiving menstruation as a barrier independent of measurable physiological changes [13]. This highlights the necessity of integrating perceptual and cultural considerations alongside physiological monitoring, enabling coaches and support staff to design training programs that address both objective and subjective elements of performance [16].

Furthermore, training load, recovery, and injury risk in female athletes are intricately linked to hormonal status and energy availability. Research suggests that certain menstrual phases may increase musculoskeletal injury risk, particularly in structures such as the anterior cruciate ligament, though findings remain nuanced and context-dependent [10,11]. Recovery processes, including glycogen replenishment, inflammatory responses, and sleep quality, are also influenced by hormonal fluctuations, emphasizing the importance of individualized load management strategies [19,21]. The advent of wearable technologies has facilitated continuous monitoring of these variables, allowing for tailored interventions that support performance while minimizing fatigue and injury risk [16,17,25]. By combining technological insights with evidence-based coaching strategies, athletes and support teams can adopt a more precise, data-informed approach to training.

Environmental and nutritional contexts further modulate female athlete performance. Thermoregulatory responses differ across menstrual phases, with core temperature elevations during the luteal phase potentially impacting performance in hot conditions [14]. Additionally, micronutrient deficiencies, such as iron insufficiency, can affect oxygen transport, endurance capacity, and fatigue resistance, particularly in female athletes [21]. Implementing context-specific nutritional strategies alongside monitoring tools such as session-RPE allows coaches and practitioners to optimize training load, recovery, and overall performance [15]. Collectively, these factors demonstrate the importance of individualized, environment-sensitive approaches in female sports science.

In the Thai context, integrating physiological research with applied sport practices provides valuable insights for athlete development and industry resilience. Vorramate and Chankuna [22] highlighted high-performance strategies for Thai badminton players preparing for the Tokyo 2020 Olympics, emphasizing structured long-term development, individualized training, and scientific monitoring. Concurrently, Chankuna et al. [23] documented the COVID-19 pandemic's disruptive effects on the Thai sport industry, reinforcing the need for adaptive strategies that safeguard athlete health and performance while supporting industry stability. These findings illustrate the necessity of combining global sport science insights with local contextual understanding to advance female athlete development in Thailand and other Southeast Asian countries.

Overall, advancing female athlete performance requires integrative, interdisciplinary approaches that consider hormonal dynamics, energy availability, psychosocial factors, recovery strategies, environmental stressors, and technological innovations. By emphasizing individualized monitoring, culturally sensitive coaching, and evidence-based interventions, sport science can optimize both performance and health outcomes for female athletes. Continued research that bridges laboratory findings, applied practice, and local contexts will be essential for developing robust strategies to support women in sport, from grassroots participation to elite international competition [1–25].

OBJECTIVE

The overarching aim of this study is to examine the physiological, hormonal, and performance-related dynamics of female athletes beyond the menstrual cycle, with the goal of developing integrative approaches that optimize training, recovery, and health outcomes. Specifically, this study seeks to:

1. Investigate the influence of menstrual cycle phases on physiological performance indicators and recovery patterns, including maximum oxygen uptake (VO_{2max}), heart rate variability (HRV), core temperature, and muscle contractility, while accounting for inter-individual variability among Thai female athletes.

2. Examine the relationship between energy availability, perceived exertion, and injury incidence, focusing on how Relative Energy Deficiency in Sport (RED-S) affects physiological strain and training outcomes.

3. Evaluate the role of wearable monitoring and individualized training strategies in enhancing data-driven decision-making for female athletes, with practical implications for cycle tracking, recovery management, and evidence-based coaching.

By addressing these objectives, the study provides an empirically grounded framework for optimizing training and health among female athletes, contributing to the advancement of sport science practice in Thailand and beyond.

METHODS

This study employed a mixed-methods design to investigate physiological, hormonal, and performance dynamics of female athletes across different menstrual cycle phases. The approach integrated quantitative assessments of performance, physiological markers, and wearable monitoring data with qualitative insights from athlete-reported experiences and perceptions, enabling triangulation and a holistic understanding of the interplay between hormones, training load, recovery, and psychosocial factors [1,4,16].

Population and Sampling Technique

The study population consisted of female athletes from two universities in Thailand, totaling 233 participants. Of these, 166 athletes were enrolled from Thailand National Sports University, Chiang Mai campus, and 67 athletes from Chandrakasem Rajabhat University. To ensure adequate representation of trained athletes, purposive sampling was applied to select 60 participants from the total population. The selected athletes were eumenorrheic female athletes aged 18–30 years, meeting the criteria of regular menstrual cycles (24–35 days), consistent training for at least six months, and no current pregnancy. Athletes using hormonal contraceptives were excluded from the hormonal phase analysis to ensure accuracy in identifying natural menstrual fluctuations. This exclusion criterion helped maintain a homogeneous sample for evaluating physiological and autonomic responses among eumenorrheic female athletes [1,22,23].

Quality of Quantitative and Qualitative Instruments

To ensure validity and reliability, all instruments were standardized and calibrated. VO_{2max} and heart rate variability (HRV) devices were tested for measurement accuracy with coefficients of variation (CV) $<5\%$. Tensiomyography reliability was confirmed with intra-class correlation coefficients (ICC) >0.90 for repeated measures (24). DXA measurements had ICC >0.95 for lean mass and bone density. Dietary logs were validated using the multiple-pass recall method, with inter-rater agreement >85% for energy and macronutrient analysis.

For qualitative data, trustworthiness was ensured through credibility, transferability, dependability, and confirmability [16]. Two independent coders analyzed transcripts, achieving inter-coder reliability >85%. Member checking was applied to confirm interpretations with participants. Triangulation with quantitative findings enhanced the overall validity.

Conceptual Framework for Qualitative Theme Acquisition

The qualitative analysis followed a systematic thematic framework. First, transcripts were coded inductively to identify meaningful units related to performance, hormonal effects, energy management, recovery, and psychosocial experiences. Codes were grouped into categories, which were iteratively reviewed and refined into themes reflecting common patterns and divergences across participants. These themes were then mapped to the conceptual framework linking menstrual cycle phases, hormonal dynamics, training load, recovery, and psychosocial influences. This framework allowed the integration of qualitative and quantitative findings, providing actionable insights for athlete-centered interventions [13,16].

Ethical Considerations

All participants provided informed consent, and the study adhered to the Declaration of Helsinki and local regulations. Confidentiality was maintained through anonymized data storage. Participants could withdraw at any time without penalty [1,2,23].

Data Collection

Data collection was conducted over two complete menstrual cycles to capture intra- and inter-individual variability. Menstrual cycle phases were verified using triangulated methods: self-reported cycle tracking, basal body temperature, and salivary hormone assays for estrogen and progesterone. This multimodal verification minimized misclassification and enhanced reliability [4,6,7].

- Quantitative data collection comprised five major measurement categories, each described below to ensure clarity and reproducibility:

1) Physiological performance was assessed through VO_{2max} (ml/kg/min) using the Bruce treadmill protocol with a Cosmed Quark metabolic analyzer (Italy). Lactate threshold was determined via fingertip blood samples analyzed using a YSI 2300 lactate analyzer (USA). Heart rate variability (HRV) was recorded using the Polar H10 sensor (Finland), analyzed through the Root Mean Square of Successive Differences (RMSSD, ms) index, and core temperature was monitored using the ThermoScan Pro 6000 thermometer (USA) during standardized endurance and intermittent exercise protocols.

2) Musculoskeletal assessment included measurement of skeletal muscle contractile properties using Tensiomyography (TMG-BMC Ltd., Slovenia) and body composition (bone mineral density, fat mass, lean mass) via dual-energy X-ray absorptiometry (DXA) following manufacturer calibration procedures [21,24].

3) Energy availability (EA) was calculated as energy intake (kcal/kg FFM/day) minus exercise energy expenditure, derived from dietary logs, resting metabolic rate, and wearable-based activity tracking. EA

values were interpreted according to Relative Energy Deficiency in Sport (RED-S) risk thresholds, as recommended by the International Olympic Committee consensus statement [12].

4) Training load monitoring was performed using the Session-RPE (Rate of Perceived Exertion) scale combined with data from wearable devices that captured heart rate, movement, and workload parameters [15,17,25].

5) Injury surveillance involved prospective documentation of musculoskeletal complaints and confirmed injuries across menstrual phases, allowing correlation analyses between energy availability, HRV, and injury incidence [10,11].

All physiological and performance measurements were conducted under standardized morning conditions following an overnight fast of at least 8 hours. VO_{2max} and lactate threshold were measured during exercise testing using the Bruce treadmill protocol, whereas HRV, core temperature, muscle contractility, and energy availability were assessed at rest prior to exercise to ensure valid baseline physiological values. VO_{2max} (ml/kg/min) was defined as the sole performance variable, representing maximal oxygen uptake, while other parameters such as HRV, core temperature, and muscle contractility were considered physiological and autonomic response indicators rather than direct measures of performance.

- Qualitative data were collected through structured interviews and focus groups, exploring athlete perceptions of menstrual cycle effects, training adaptation, and psychosocial experiences. Sessions were audio-recorded, transcribed, and anonymized.

Data Analysis

Quantitative data were analyzed using IBM SPSS Statistics version 21.0 (IBM Corp., Armonk, NY, USA). Repeated-measures ANOVA was employed to examine differences across menstrual phases, with Bonferroni post hoc tests applied to identify specific pairwise differences. Mixed-effects models were additionally used to account for inter-individual variability and covariates, including age, training history, and contraceptive use [4,7]. Pearson's correlation test (α = 0.05) was conducted to assess linear relationships among energy availability, heart rate variability (HRV), perceived exertion, and injury incidence [11,12]. Qualitative data were analyzed via thematic analysis using NVivo 14, and findings were triangulated with quantitative results to identify convergent and divergent patterns, enhancing interpretability and applicability [13,16]. An overview of the research protocol is presented in Table 1.

Table 1 Research Protocol Overview

Phase / Component	Purpose	Participants & Sampling	Variables / Instruments	Procedure	Data Analysis
Phase 1: Participant Recruitment and Screening	Identify eligible female athletes and record baseline characteristics	60 athletes (43 from TNSU Chiang Mai, 17 from Chandrakasem Rajabhat University); purposive sampling from a population of 233	Screening form (age, menstrual regularity, contraceptive use, training experience)	Eligibility verified by menstrual regularity (28 ± 4 days), absence of hormonal contraceptives, and informed consent	Descriptive statistics (mean ± SD)
Phase 2: Physiological Measurement	Assess physiological and autonomic responses across menstrual phases	Same 60 participants, measured in follicular, ovulatory, and luteal phases	- VO_2max: Bruce protocol on treadmill (Cosmed Quark, Italy) - HRV: Polar H10 (Finland), RMSSD (ms) - Core temperature: ThermoScan Pro 6000 (USA) - Muscle contractility: Tensiomyography TMG-BMC (Slovenia) - Energy availability: kcal/kg FFM/day (diet logs + training load)	Measurements conducted under resting conditions, morning sessions, after overnight fast. Menstrual phase verified by basal temperature and self-reported symptoms.	Repeated-measures ANOVA, Bonferroni post hoc, Pearson correlation (α = 0.05), SPSS 21.0
Phase 3: Qualitative Data Collection	Explore athlete perceptions and contextual experiences	Subsample of 12 athletes (diverse by sport and menstrual pattern)	Semi-structured interview guide	Interviews and focus groups recorded and transcribed; themes derived through coding (open ⟶ axial ⟶ selective)	Thematic analysis using NVivo 14
Phase 4: Integration and Interpretation	Integrate quantitative and qualitative findings to propose applied recommendations	Full dataset	Triangulated dataset (performance, HRV, RPE, injury, thematic categories)	Mixed-methods integration based on complementarity design	Joint display synthesis; interpretation aligned with research objectives

RESULTS

Participant Characteristics

A total of 60 female athletes participated in the study, with a mean age of 22.4 ± 2.6 years and an average training history of 6.8 ± 2.1 years. Of these, 43 athletes (72%) were from Thailand National Sports University, Chiang Mai campus, and 17 athletes (28%) were from Chandrakasem Rajabhat University. Fifteen participants (25%) were using hormonal contraceptives. Body composition analysis showed mean body fat of 21.3 ± 3.7% and lean mass of 46.2 ± 4.5 kg. Baseline energy availability averaged 38.7 ± 6.1 kcal/kg FFM/day, with 20% of athletes classified as at risk for Relative Energy Deficiency in Sport (RED-S) based on established thresholds [12].

Quantitative Metrics Across Menstrual Phases

VO_{2max} ml/kg/min) was defined as the sole performance indicator, evaluated across the follicular, ovulatory, and luteal phases. Results showed no significant differences in VO_{2max} between phases ($p > 0.05$), confirming that aerobic performance remained stable throughout the menstrual cycle. Similarly, lactate threshold (mmol/L) showed no significant variation across the three phases. In contrast, several physiological and autonomic response variables exhibited meaningful fluctuations. Heart rate variability (HRV) was modestly reduced in the luteal phase compared to the follicular phase (mean difference = 4.2 ms, $p = 0.042$), while core temperature was significantly higher during the luteal phase (37.4 ± 0.3 °C) relative to the follicular phase (36.9 ± 0.2 °C, $p < 0.001$), consistent with progesterone-induced thermogenic effects [7,14]. Muscle contractility, assessed by tensiomyography, showed minor, non-significant variation, with slightly slower gastrocnemius contraction velocity observed in the early follicular phase ($p = 0.068$). These results suggest that while aerobic capacity remains unchanged, autonomic and thermoregulatory responses fluctuate across menstrual phases. All measured outcomes are summarized in Table 2.

Table 2 Outcomes Metrics Across Menstrual Phases

Parameters	Follicular Phase	Ovulatory Phase	Luteal Phase	p-value
VO_{2max} (ml/kg/min)	52.3 ± 4.6	52.8 ± 4.3	52.1 ± 4.5	0.61
Lactate Threshold (mmol/L)	3.2 ± 0.5	3.4 ± 0.4	3.5 ± 0.6	0.57
HRV (RMSSD, ms)	52.8 ± 7.1	51.9 ± 6.9	48.6 ± 7.2[c]	0.042*
Core Temp (°C)	36.9 ± 0.2[a]	37.2 ± 0.3	37.4 ± 0.3[c]	0.001*
Gastrocnemius Contractility (mm/ms)	9.2 ± 1.1	9.5 ± 1.0	8.9 ± 1.2	0.068

* p-value < 0.05; [a] = Follicular Phase differs from Ovulatory Phase; [b] = Ovulatory Phase differs from Luteal Phase; [c] = Follicular Phase differs from Luteal Phase; RMSSD = Root Mean Square of Successive Differences; HRV values in this table represent mean RMSSD (ms) measured across menstrual phases (follicular, ovulatory, and luteal) to illustrate phase-related autonomic variations.

Energy Availability and RED-S Risk

Energy intake relative to expenditure varied among participants, with 12 athletes (20%) identified at risk for RED-S. These athletes demonstrated slightly lower HRV and slightly higher perceived exertion during training, although VO_{2max} and lactate thresholds were not significantly different (Table 3). Correlation analysis (Table 4) indicated moderate associations between energy availability and HRV (r = 0.41, p = 0.03), as well as between energy availability and injury incidence (r = -0.38, p = 0.04), consistent with literature linking low energy availability to autonomic and musculoskeletal alterations [11,12].

Table 3 Energy Availability and RED-S Risk Among Female Athletes

Variables	Total Sample (n=60)	At Risk for RED-S (n=12)	Not at Risk (n=48)	p-value
Energy Availability (kcal/kg FFM/day)	38.7 ± 6.1[a]	30.2 ± 3.5[b]	40.9 ± 5.4[c]	0.001*
HRV (RMSSD, ms)	50.8 ± 7.2	46.1 ± 6.8[b]	52.0 ± 6.9	0.03*
Perceived Exertion (session-RPE)	6.8 ± 1.1	7.4 ± 1.0[b]	6.6 ± 1.1	0.04*
Injury Incidence (events/cycle)	0.42 ± 0.25[a]	0.63 ± 0.28[b]	0.37 ± 0.21	0.04*

* p-value < 0.05; [a] = Total Sample differs from At Risk for RED-S; [b] = At Risk for RED-S differs from Not at Risk; [c] = Total Sample differs from Not at Risk; RMSSD = Root Mean Square of Successive Differences; HRV values in this table represent mean RMSSD (ms) categorized by energy availability status, comparing athletes at risk vs. not at risk for Relative Energy Deficiency in Sport (RED-S).

Table 4 Correlation Matrix among Energy Availability, HRV, Perceived Exertion, and Injury Incidence in Female Athletes

Variables	Energy Availability	HRV	Perceived Exertion	Injury Incidence
Energy Availability	1.00	-	-	-
HRV	0.41*	1.00	-	-
Perceived Exertion	–0.41*	–0.49*	1.00	-
Injury Incidence	–0.38*	–0.44*	0.36*	1.00

* p-value < 0.05

Qualitative Thematic Findings

Thematic analysis of interviews and focus groups revealed four major themes:

1. Perceived menstrual impact on training and performance: Athletes often reported subjective fatigue, reduced concentration, or altered motivation during the early follicular phase, despite minimal objective performance changes.

2. Adaptive strategies and self-monitoring: Participants described adjusting training intensity, hydration, and nutrition based on cycle tracking, demonstrating proactive self-regulation.

3. Psychosocial and cultural influences: Social expectations, stigma, and coach communication affected confidence and willingness to disclose menstrual-related issues.

4. Integration of technology for individualized planning: Athletes valued wearable devices and mobile apps for monitoring load, recovery, and cycle phases, supporting personalized adjustments and injury prevention.

Table 5 provides a summary of qualitative themes with representative quotes.

Table 5 Summary of Qualitative Themes and Representative Quotes

Theme	Representative Quote
Menstrual impact on training	*"I feel slower and more fatigued during my period, even if my times don't drop much."*
Adaptive strategies and self-monitoring	*"I track my cycle to adjust my practice load and recovery days."*
Psychosocial and cultural influences	*"Some coaches don't ask about periods, so I just push through."*
Technology integration	*"Using wearables helps me know when to rest or push harder."*

Key Integrations

Figure 1 presents a conceptual framework integrating quantitative and qualitative findings, showing how menstrual cycle, hormonal changes, energy availability, training load, and psychosocial factors interact to affect performance and applied recommendations.

The integration of quantitative and qualitative data provides a nuanced understanding of female athlete performance. While objective performance metrics showed modest variations across menstrual phases, subjective perceptions, psychosocial influences, and self-regulatory strategies played critical roles in how athletes managed training and recovery. Wearable monitoring enabled individualized adjustments, supporting both performance optimization and injury prevention. These results highlight the importance of integrating hormonal, physiological, and psychosocial data to inform athlete-centered interventions [1–25,16,22,23].

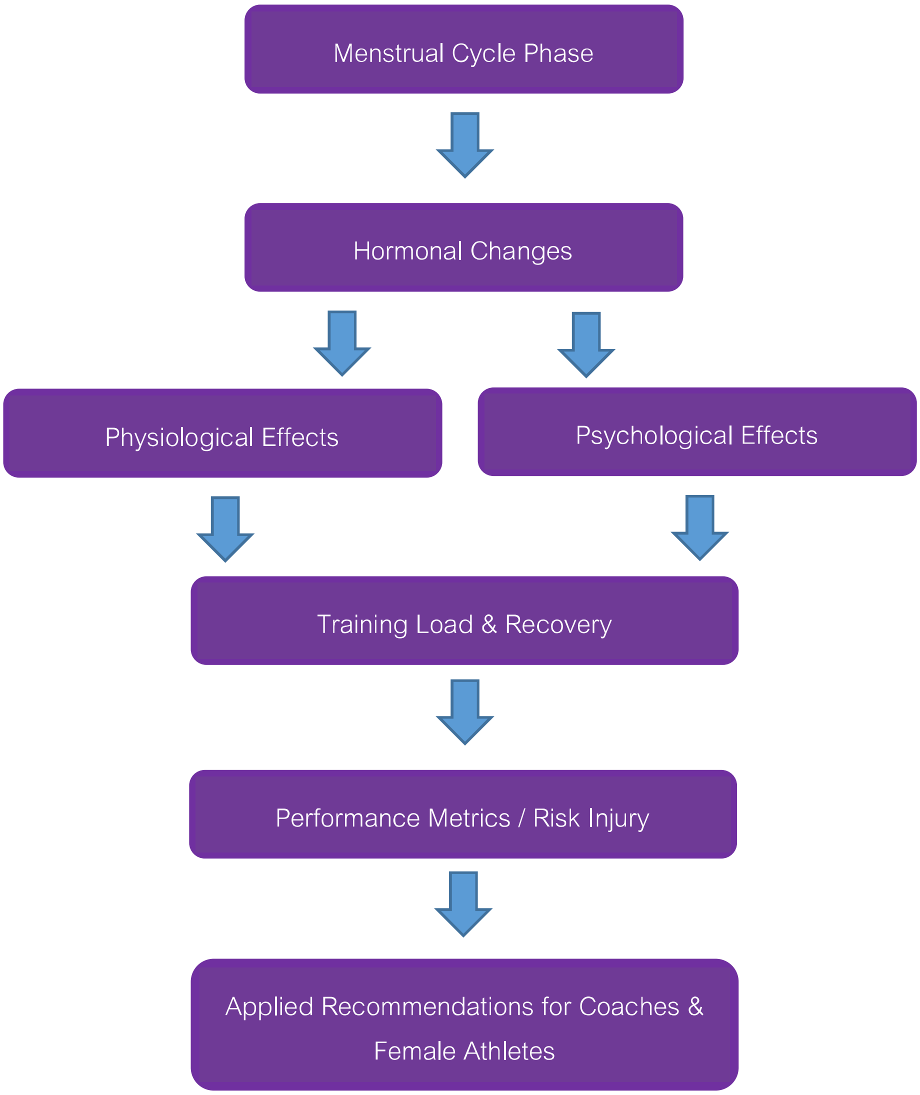

Figure 1 Conceptual Framework Integrating Quantitative and Qualitative Findings

Source: Author

DISCUSSION

The purpose of this study was to examine the physiological and autonomic responses of Thai female athletes across menstrual phases, focusing on measurable outcomes that address three key objectives: (1) to assess the influence of menstrual cycle phases on physiological performance and recovery, (2) to analyze the relationship between energy availability and injury risk, and (3) to evaluate the usefulness of wearable-based individualized monitoring in training management.

Regarding the first objective, the results confirmed that aerobic performance, measured by VO_{2max}, remained stable across menstrual phases, supporting previous meta-analyses that found minimal variation in endurance capacity throughout the cycle [4]. However, physiological responses such as HRV and core temperature showed significant phase-related changes, with lower HRV and higher core temperature during the luteal phase. These findings are consistent with Janse de Jonge et al. [6] and Matsuda et al. [7], who reported that hormonal fluctuations influence thermoregulation and autonomic activity more than aerobic performance itself. Importantly, intra-individual variability was observed in HRV and core temperature, reflecting how each athlete's autonomic system adapts differently across phases. This variability indicates that even within the same menstrual stage, individual recovery capacity and physiological strain may differ due to unique hormonal sensitivities or training stress. Meanwhile, inter-individual variability was evident in VO_{2max} and energy availability, attributable to differences in training history, sport discipline, and fitness level among participants. Recognizing these sources of variability is crucial for interpreting group-level findings and tailoring training to individual needs.

For the second objective, the interaction between energy availability and recovery-related variables revealed that approximately 20% of athletes were at risk for Relative Energy Deficiency in Sport (RED-S). These athletes exhibited lower HRV, higher perceived exertion, and greater injury incidence—findings that align with Tenforde et al. [11] and the IOC consensus on RED-S [12]. Although reduced energy availability did not directly impair VO_{2max}, it contributed to subtle physiological strain and injury vulnerability. This underscores that aerobic capacity alone is not a sufficient indicator of health; instead, continuous monitoring of energy balance and recovery markers is necessary to detect early risk.

The third objective focused on evaluating wearable technologies and individualized monitoring strategies. The integration of heart rate, temperature, and workload data from wearable devices allowed more precise interpretation of athletes' physiological states. Similar to Seçkin et al. [17] and Preatoni et al. [25], the present study found that wearable data complemented athlete self-reports, bridging objective and subjective indicators of fatigue and readiness. Such integration enhances real-time decision-making for training adjustments and recovery scheduling.

Overall, these findings confirm that female athletes maintain stable aerobic performance across menstrual phases, but their physiological and autonomic responses exhibit both intra- and inter-individual variability. Energy availability emerged as a critical determinant of recovery and injury prevention, while wearable monitoring proved to be a practical tool for individualized load management. For Thai athletes, these insights have direct implications for developing context-sensitive performance programs that combine physiological tracking and athlete education. By embracing individualized variability rather than averaging it out, sport practitioners can move toward more precise, evidence-based strategies that promote both performance optimization and long-term athlete well-being.

However, this study has several limitations that should be acknowledged when interpreting the findings. First, hormonal concentrations such as estrogen and progesterone were not directly measured through biochemical assays; therefore, menstrual phases were identified using self-reported symptoms and basal temperature tracking. This approach may introduce minor classification error and limits the precision of hormonal interpretation. Second, the relatively small sample size of sixty participants, although sufficient for correlation analysis, may restrict the generalizability of results to broader athletic populations. Third, participants were recruited exclusively from university sport programs, representing a specific demographic with structured training schedules and academic commitments. Consequently, the findings may differ for professional or recreational female athletes who experience different training intensities and environmental exposures. Future research should include larger, more diverse samples and integrate direct hormonal and metabolic assays to strengthen causal inference and improve external validity.

Practical Suggestion

The findings of this study provide evidence-based guidance for improving female athlete management in Thailand and similar contexts. Practical recommendations are as follows:

1. Individualized Monitoring

Athletes should track menstrual cycles through basal body temperature and self-reported symptoms together with HRV and core temperature data. This individualized approach enables coaches to align training and recovery with hormonal variations and helps reduce misconceptions about performance.

2. Energy Availability Screening

As 20 percent of athletes were found to be at risk for RED-S, regular monitoring of energy intake and expenditure is essential. Education on proper nutrition and balanced fueling can prevent long-term health issues related to bone strength, metabolism, and injury.

3. Wearable Technology Integration

Wearable devices are effective for tracking HRV, core temperature, and workload. Data should be interpreted by trained professionals and combined with session-RPE scores to manage recovery and avoid overtraining.

4. Supportive Coaching Culture

Psychological and cultural barriers around menstruation require attention. Coach education, especially for male coaches, should focus on open and respectful communication to build trust and reduce stigma.

5. Institutional and Policy Applications

Sports universities and federations should integrate menstrual health tracking, RED-S screening, and wearable systems into athlete development programs. Policies should align with IOC RED-S recommendations and promote gender-responsive monitoring standards.

In conclusion, combining physiological tracking, energy assessment, wearable monitoring, and psychosocial support can reduce injury risk and enhance sustainable, evidence-based athlete development.

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