

Hormonal Fluctuations (Estrogen & Progesterone) and Their Impact on Muscle Recovery and Fatigue

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Abstract:

This conceptual research paper investigates the impact of hormonal fluctuations, particularly estrogen and progesterone, on muscle recovery and fatigue in female athletes. Estrogen is widely recognized for its protective and regenerative effects, while progesterone is associated with increased fatigue perception and impaired neuromuscular coordination. As a result of synthesizing existing literature, identifying research gaps, and proposing a methodological framework, the current paper emphasizes the significance of sex-specific approaches in exercise physiology and science of recovery.

Key Words: hormonal fluctuations, protective, Estrogen, progesterone, neuromuscular coordination.

INTRODUCTION:

Muscle recovery and fatigue are central to athletic performance, rehabilitation, and long-term injury prevention. Recovery encompasses the physiological processes that restore muscle function following exercise, including tissue repair, removal of metabolic byproducts, and restoration of energy substrates. Fatigue, on the other hand, represents a turn down in muscular performance capacity, often influenced by metabolic stress, neuromuscular factors, and psychological perception while these processes are common to all athletes, female athletes experience unique physiological variations due to cyclical hormonal fluctuations across the menstrual cycle.

The menstrual cycle is separated into distinct phases follicular, ovulatory, and luteal each characterized by varying concentrations of estrogen and progesterone. Estrogen peaks during the late follicular phase and is associated with beneficial effects on muscle tissue, including enhanced collagen synthesis, reduced oxidative stress, and improved vascularization (Tiidus, 2000). These properties suggest that estrogen may play a protective role against exercise-induced muscle damage and accelerate recovery. In dissimilarity, progesterone rises during the luteal phase and has been linked to increased fatigue perception, altered thermoregulation, and impaired neuromuscular coordination (Janse de Jonge, 2003). This hormonal interplay creates a dynamic physiological environment that may significantly influence training outcomes and recovery strategies.

Despite these well-documented hormonal fluctuations, exercise science research has historically focused on male physiology, often generalizing findings to female athletes without accounting for sex-specific differences. This oversight has led to training protocols and recovery models that may not fully optimize female performance. For example, studies have shown that female athletes may experience greater susceptibility to musculoskeletal injuries, particularly anterior cruciate ligament (ACL) tears, during phases of the cycle when estrogen levels are elevated (Hewett et al., 2007). Such findings underscore the need to integrate hormonal considerations into sports medicine and training frameworks.

Recent advances in sports endocrinology have begun to highlight the importance of tailoring exercise and recovery strategies to menstrual cycle phases. Hackney (2020) emphasizes that performance outcomes vary across the cycle, with high-intensity exercise often better tolerated during the follicular phase, while endurance and recovery may be compromised during the luteal phase. Elite female athletes have increasingly adopted cycle-based training approaches, adjusting workloads and recovery modalities to align with hormonal profiles. This emerging practice reflects a growing recognition that sex-specific physiology must be central to sports science research and application.

By examining the interaction between estrogen and progesterone and their impact on muscle recovery and fatigue, this paper seeks to contribute to a more inclusive understanding of exercise physiology. Such insights hold practical implications for designing menstrual cycle specific training regimens, optimizing recovery strategies, and promoting gender equity in sports science research. Ultimately, integrating hormonal considerations into athletic programming may enhance performance, reduce injury risk, and advance the broader field of personalized medicine in sport.

Rationale

Understanding hormonal influences on recovery can help design personalized training programs for women. Current protocols often overlook menstrual cycle phases, potentially leading to suboptimal performance and higher injury risks. Addressing this gap is essential for advancing sports science and promoting gender-inclusive research.

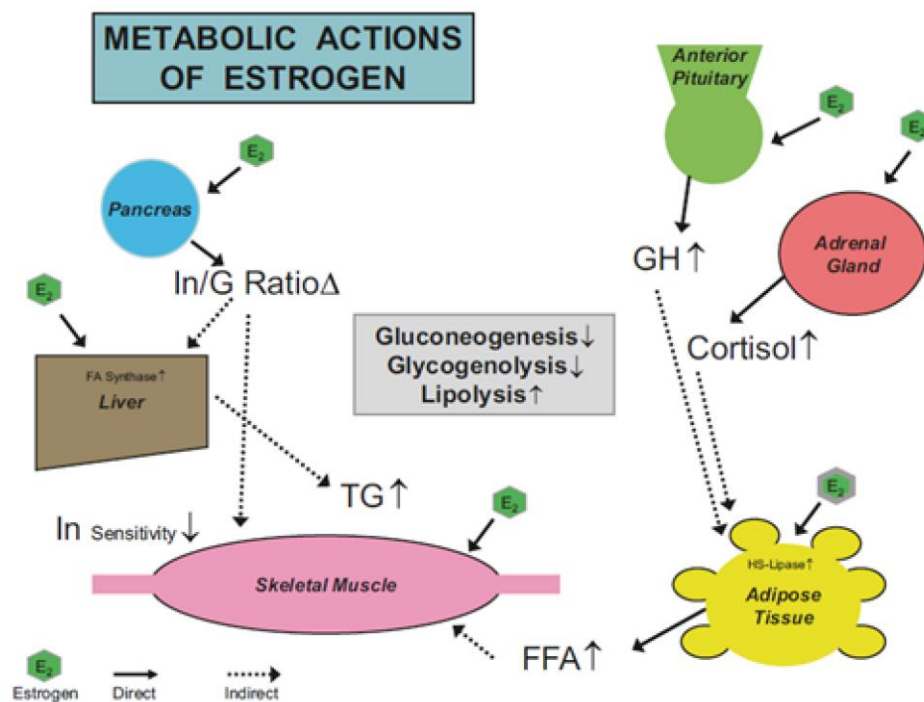
Review of Literature

Estrogen's Role

Estrogen is increasingly recognized as a critical regulator of skeletal muscle health. Beyond its systemic effects, skeletal muscle itself can synthesize “myogenic estrogen,” which acts locally to regulate muscle metabolism and repair. This autocrine/paracrine estrogen enhances mitochondrial function, promotes protein synthesis, and reduces inflammation, thereby accelerating recovery after exercise (Feng & Shi, 2026). Estrogen also improves vascularization, facilitating nutrient delivery and waste clearance, which are essential for recovery. In postmenopausal women, reduced estrogen levels are linked to sarcopenia, decreased muscle quality, and slower recovery, highlighting its protective role across the lifespan (Hansen, 2017).

Estrogen has been widely studied for its protective and regenerative effects on skeletal muscle. It enhances collagen synthesis, which contributes to connective tissue strength and resilience, thereby reducing the risk of musculoskeletal injuries (Tiidus, 2000). Estrogen also exhibits antioxidant properties, mitigating oxidative stress that typically arises from intense exercise. This reduction in oxidative damage helps limit muscle fiber disruption and accelerates recovery. Furthermore, estrogen has been linked to improved vascular function, facilitating nutrient delivery and waste removal during recovery phases. Collectively, these mechanisms suggest that estrogen plays a critical role in promoting muscle repair and reducing exercise-induced damage.

Figure: Mechanism of Estrogens Action



Source: Davis (2017)

Above figure illustrates the direct (—) and indirect (----) effects of estrogens (E₂) on a variety of hormones and physiological processes important to exercise energy metabolism; e.g., energy substrate availability-mobilization (Davis, 2017).

Abbreviations: FFA = free fatty acids, G = glucagon, GH = growth hormones, I insulin, TG = triglycerides. Symbols: ↑ = increase, ↓ = decrease, Δ = change.

Role of Progesterone

In contrast, progesterone has been associated with less favorable outcomes for muscle recovery. Elevated progesterone levels, particularly during the luteal phase, may impair neuromuscular coordination and increase central fatigue perception (Janse de Jonge, 2003). Progesterone influences thermoregulation, often leading to higher core body temperatures, which can exacerbate fatigue during prolonged exercise. Additionally, progesterone's effects on fluid balance and electrolyte regulation may contribute to reduced endurance capacity. These factors highlight progesterone's potential role in elevating fatigue thresholds and diminishing recovery efficiency compared to estrogen-dominant phases. Progesterone, which rises during the luteal phase, has been associated with impaired neuromuscular coordination and increased fatigue perception. It influences thermoregulation, often elevating core body temperature, which can exacerbate fatigue during prolonged exercise (Janse de Jonge, 2003). Progesterone also affects fluid balance and electrolyte regulation, potentially reducing endurance capacity. These effects suggest that progesterone may counteract some of estrogen's protective benefits, creating a hormonal environment less conducive to rapid recovery.

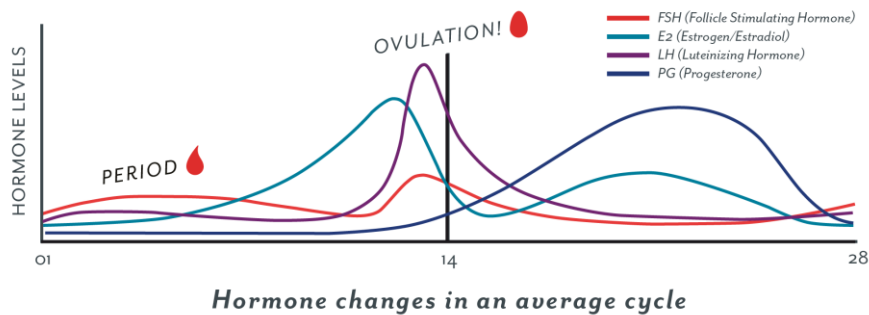
Change in progesterone levels during the menstrual cycle

Progesterone levels are not fixed. They vary throughout the menstrual cycle and can change depending on the specific phase of the cycle in any female (Endocrine Society, 2019).

Before ovulation: Progesterone levels are low at the beginning of the menstrual cycle (during your period) and remain low throughout the follicular phase, which is the time before ovulation occurs (Cleveland Clinic, 2023; Mayo Clinic Laboratories, 2022).

- **After ovulation:** Progesterone levels are highest in the middle of the luteal phase. This is after ovulation and before menstrual bleeding begins. Progesterone is produced by the corpus luteum (the structure that forms in the ovary after ovulation) (Melmed S, Polonsky KS, Larsen PR, Kronenberg HM. Williams, 2020; Hall JE. Guyton and Hall, 2021). If pregnancy does not occur, the corpus luteum begins to break down 9–10 days after ovulation, causing progesterone levels to fall and menstrual bleeding to begin (ACOG, 2020; Cleveland Clinic, 2023).

Figure: Menstrual cycle rhythmicity: metabolic patterns in healthy women.



Source: Draper CF, Duisters K, Weger B, et al. (2018)

Typical levels of progesterone during different life stages

Progesterone levels can vary from person to person, but also from cycle to cycle (Sturdee DW, et al. 2011). Differences in laboratory procedures, population served by the laboratory, and testing technique can also impact results, so results should always be interpreted using the laboratory’s reference values (Mayo Clinic Laboratories, 2022).

Here’s a progesterone levels chart to give an idea of how levels compare across different life stages (National Institutes of Health. 2021).

Table: progesterone levels chart

life stages	Quantity	levels
Pre-puberty	.07-.52 ng/mL	Low
Adult female follicular phase	.15-.70 ng/mL	Low
Adult female luteal phase	2-25 ng/mL	Intermediate
First trimester pregnancy	7.25-44 ng/mL	Intermediate
Second trimester pregnancy	19.5-82.5 ng/mL	High
Third trimester pregnancy	65-229 ng/mL	Very High
Menopause	<.4 ng/mL	Low

Source: National Institutes of Health (2021)

Cycle Phase Differences

The menstrual cycle introduces distinct physiological environments that influence recovery and fatigue. During the follicular phase, when estrogen levels are higher and progesterone remains relatively low, recovery tends to be faster, and athletes often report improved exercise tolerance. Conversely, the luteal phase, characterized by elevated progesterone, is associated with increased fatigue perception, slower recovery, and reduced neuromuscular efficiency (Hackney, 2020). These phase-dependent differences underscore the importance of considering menstrual cycle timing when designing training and recovery protocols for female athletes. The menstrual cycle introduces distinct physiological environments.

During the follicular phase, higher estrogen and lower progesterone levels support faster recovery, reduced muscle soreness, and improved exercise tolerance. Conversely, the luteal phase, dominated by progesterone, is associated with slower recovery, heightened fatigue perception, and reduced neuromuscular efficiency (Hackney, 2020). Recent systematic reviews confirm that these phase-dependent differences are consistent across multiple studies, though individual variability remains high (Kodete et al., 2024).

Life Stage Considerations

Hormonal influences on muscle recovery extend beyond the menstrual cycle. During adolescence, rising estrogen levels contribute to muscle growth and improved strength. Pregnancy introduces substantial hormonal shifts, with estrogen and progesterone elevated, altering muscle metabolism and recovery dynamics. Menopause, characterized by a sharp decline in estrogen, is linked to muscle atrophy, reduced protein synthesis, and increased fatigue, underscoring the importance of estrogen replacement or exercise interventions to maintain muscle health (Hansen, 2017).

Research Gap

Few studies provide mechanistic insights into how estrogen and progesterone interact to influence recovery. Longitudinal and controlled trials on female athletes are scarce, limiting evidence based recommendations found.

Research Question

How do fluctuations in estrogen and progesterone across the menstrual cycle impact muscle recovery and fatigue in female athletes?

Objectives

Objective of this study was to conceptually evaluate how estrogen and progesterone fluctuations affect muscle recovery and fatigue during the menstrual cycle. Also to analyze estrogen's role in muscle repair and oxidative stress reduction.

Research Methodology

This study adopts a conceptual (theoretical) research design, focusing on the systematic review and synthesis of existing scientific literature. It does not involve primary data collection but instead integrates findings from previously published studies to develop a comprehensive understanding of how hormonal fluctuations influence muscle recovery and fatigue. A qualitative, analytical approach is used to examine and interpret relationships between estrogen, progesterone, and physiological responses related to muscle repair and fatigue. The study emphasizes theory-building and conceptual clarification. Data for this study are collected from secondary sources, including peer-reviewed journal articles, medical and physiology textbooks, systematic reviews, publications from reputable organizations such as National Institutes of Health and World Health Organization and academic databases.

Argument

Estrogen's antioxidant and regenerative properties may accelerate recovery, while progesterone's neuromuscular effects contribute to fatigue. This interplay suggests that training intensity should be adjusted according to menstrual phases high-intensity work during follicular phases and recovery-focused protocols during luteal phases. Such cycle-based training could optimize performance and reduce injury risks.

Conclusion

Hormonal fluctuations significantly influence muscle recovery and fatigue in female athletes. Estrogen supports recovery, while progesterone elevates fatigue perception. Recognizing these dynamics enables personalized training strategies, potentially improving performance and reducing injury risks. This conceptual framework highlights the need for longitudinal studies to validate these findings and inform evidence-based practice.

Suggestions

Menstrual cycle based training programs is suggested for female athletes which will help them to their muscle recovery and fatigue. There should be integration of hormonal monitoring into athlete management. Further researcher should be encouraged longitudinal and mechanistic studies.

Limitations

Despite these insights, current literature is limited in scope. Most studies are short-term, observational, and conducted on small sample sizes, often failing to capture the longitudinal impact of hormonal fluctuations across multiple cycles. Furthermore, many investigations rely on self-reported menstrual phases rather than precise hormonal assays, reducing accuracy. There is also a lack of mechanistic studies exploring how estrogen and progesterone interact with other hormones such as cortisol and testosterone in influencing recovery. These limitations highlight the need for more comprehensive, controlled, and long-term studies focusing specifically on female athletes. Since the present study was conceptual in nature so there is requirement of empirical validation in the part of conceptual framework. Another limitation is that variability in menstrual cycles in different female athletes may affect the generalization of the results.

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