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NARRATIVE REVIEW

Training in Sync with the Cycle? The Impact of Hormonal Fluctuations During the Menstrual Cycle on Knee Joint Stability and ACL Injuries

a narrative review

HIGHLIGHTS

- Female athletes are 2–10× more likely to suffer non-contact ACL tears than male athletes, with anatomical, neuromuscular and hormonal mechanisms acting in combination.

- The late follicular and ovulatory phases coincide with peak estrogen, increased anterior knee laxity, and reduced neuromuscular control, making them the highest-risk window for ACL injury.
- Manual orthopedic tests are insufficient to detect cycle-related ligament changes; objective biomechanical instrumentation is required for valid risk assessment.
- Oral contraceptives partially reduce passive ligament laxity but do not correct neuromuscular deficits and carry systemic risks, so their use for injury prevention requires individualized cost-benefit analysis.
- Effective ACL injury prevention in female athletes must adopt a multidimensional, individualized approach integrating menstrual history, anatomical traits, neuromuscular control and biomechanical screening.

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ABSTRACT

BACKGROUND: Anterior Cruciate Ligament injuries represent a significant "epidemic" in sports medicine, disproportionately affecting female athletes. Women tear their ACL 2 to 10 times more often than men participating in the same sports. This disparity suggests that beyond anatomical and biomechanical differences, unique biological factors — specifically hormonal fluctuations and their impact on ligament structure — play a critical role in injury susceptibility.

AIM: The aim of this study was to conduct an analysis of the publications from the last decade regarding the influence of the menstrual cycle, sex hormones and oral contraceptives on knee joint laxity and ACL injury risk.

MATERIALS AND METHODS: A comprehensive PubMed literature search (2014–2024) was conducted, only clinically relevant, English, free full-text articles were included, supplemented by foundational studies.

RESULTS: A total of 17 original studies were included, 4 review studies have been inspected for a better understanding of older research. The analysis confirms that the pre-ovulatory and ovulatory phases are associated with increased anterior knee laxity due to peak estrogen levels. However, recent evidence suggests that increased laxity does not always result in altered biomechanics in elite athletes due to neuromuscular compensation.

CONCLUSIONS: Current evidence identifies the late follicular and ovulatory phases as the period of highest ACL injury risk, driven by a simultaneous decline in both passive joint stability and active motor control. Importantly, utilizing oral contraceptives does not offer a complete solution, as they only address passive laxity while leaving neuromuscular deficits unresolved and posing systemic risks. Future injury prevention must therefore adopt a multidimensional approach, utilizing individualized screening that integrates menstrual history, specific anatomical predispositions, and objective biomechanical assessments.

KEYWORDS Anterior Cruciate Ligament; ACL injury; knee laxity; menstrual cycle; oral contraceptives; female athlete; sex hormones; estrogens; relaxin

1. INTRODUCTION

With the growing participation of women in both competitive and recreational sports, there has been an alarming increase in severe orthopedic injuries, particularly anterior cruciate ligament (ACL) tears [1]. Statistics and clinical studies show that female athletes are 2 to 10 times (depending on the study group, type of discipline etc.) more likely to suffer a non-contact ACL tear compared to men [2–8]. This disproportionately high injury rate makes ACL tears one of the most pressing challenges in modern sports medicine, significantly affecting athletes' careers, performance and long-term joint health [4,9].

Female athletes seem to have disproportionately higher rates of ACL injury in the follicular and ovulatory phases of the menstrual cycle compared to the luteal phase [9,10]. The problem of this high injury rate in women is multifactorial and stems from a complex interaction of anatomical differences, neuromuscular control patterns and fluctuating hormonal profiles [3,7,11,12]. Anatomical predispositions, such as a wider pelvis and inherent differences in tendon and ligament properties, alter the baseline mechanical stress placed on the female knee. Functionally, female athletes often exhibit faulty movement patterns during high-impact tasks — such as quadriceps dominance and dynamic knee valgus — which drastically increase the loading on the ACL [1,4,6,11]. Furthermore, physiological changes throughout the menstrual cycle, including variations in estrogen and relaxin levels, have been shown to temporarily alter joint laxity, tissue stiffness and movement kinematics [4,13–16].

Despite comprehensive research on these individual factors, the medical community still lacks clear, unified prevention guidelines, as findings regarding the exact impact of hormonal phases, muscle fatigue and environmental factors remain inconsistent across different studies [5]. Additionally, even after successful surgical reconstruction, women often retain poor movement strategies and altered biochemical markers, exposing them to high risk of re-injury [4]. This significant gap in knowledge and the absence of standardized, gender-specific return-to-play protocols justify a deep, integrated analysis of these risk factors [5,8].

The main goal of this paper is to analyze the newest publications to comprehensively evaluate the anatomical, biomechanical and endocrine factors that cause the higher risk of non-contact ACL injuries in women.

Therefore, this study aims to answer the following research questions:

1. How do the anatomical differences and specific movement patterns, such as quadriceps dominance and dynamic knee valgus, affect the mechanical load placed on the ACL in female athletes?

2. How do specific phases of the menstrual cycle and sex hormones, including estrogens and relaxin, modify knee joint mechanics and neuromuscular function?

3. What targeted training and prevention strategies can most effectively compensate for these physiological fluctuations and minimize the risk of both primary and secondary ACL injuries?

2. RESEARCH MATERIALS AND METHODS

2.1. Data Sources and Search Strategy

A comprehensive literature search was conducted using the PubMed (MEDLINE) database. The process was automated using a custom Python script utilizing the Entrez API (Biopython) to ensure the precision and reproducibility of the results. The search strategy employed specific keywords combined with operators (AND, OR, NOT). The search query was designed to intersect three primary domains: anatomical structure and injury, hormonal factors and cycle phases and availability.

2.2. Inclusion and Exclusion Criteria

The search algorithm was designed to retrieve all relevant publication types, including original research, systematic reviews, and meta-analyses to provide a complete overview of the current state of knowledge. Upon retrieval, the records were sorted and classified into two categories:

- Original Research: Clinical trials, cohort studies, and comparative studies were selected as the primary source of data for the analysis of injury risk and biomechanical changes.

- Secondary Research: Systematic reviews and meta-analyses were retained to establish the theoretical framework, validate findings and identify potential gaps in the literature, but were analyzed separately to avoid data duplication.

The following records were excluded during the manual screening process:

- Studies conducted on animals

- Non-English articles

- Studies not available in full-text

- Studies not directly related to the intersection of menstrual cycle, hormonal fluctuations, and musculoskeletal injury risk

Following the removal of these exclusions, all qualifying articles were manually reviewed for content relevance to the predefined research questions.

3. STATE OF KNOWLEDGE

3.1. Anatomical and Biomechanical Predispositions in Female Athletes

Female athletes present with a unique set of anatomical characteristics that fundamentally alter the mechanical environment of the knee. These structural differences — a wider Q-angle (the angle between the quadriceps muscle and the patellar tendon), a narrower intercondylar notch, and a more horizontal tibial plateau — collectively increase the valgus stress on the knee during dynamic movements [7,11]. Biomechanically, these predispositions are often manifested as quadriceps dominance and dynamic knee valgus, movement patterns that place the ACL under significantly increased strain, particularly during high-risk tasks such as jumping, cutting, and decelerating [1,4,6].

Research confirms that female athletes consistently display greater anterior tibial translation and increased knee valgus during landing compared to their male counterparts [1,11]. A cross-sectional study by Zhou et al. (2023) [11] found that female athletes demonstrate a significantly different knee kinematics profile throughout the menstrual cycle, with altered joint angles and moments that increase ACL loading. These biomechanical differences are further compounded by reduced hamstring co-activation, which means the primary dynamic stabilizer of the knee provides less counterforce to anterior tibial shear stress [6].

3.2. Hormonal Regulation: The Role of Estrogen and Relaxin

The female reproductive hormones, particularly estrogen and relaxin, exert direct and well-documented effects on musculoskeletal tissue properties. Estrogen receptors have been identified in the ACL, synovial fibroblasts, and chondrocytes, indicating that the ligament is a direct hormonal target [14,15]. The primary mechanism through which estrogen increases ACL injury risk is its inhibitory effect on collagen synthesis and its ability to decrease the activity of lysyl oxidase, the enzyme responsible for collagen cross-linking. This results in a structurally weaker and more lax ligament [14]. Lee et al. (2015) [14] directly demonstrated this in engineered ligament tissue, showing that estrogen significantly reduced the mechanical function and collagen content of the ACL.

Relaxin, a peptide hormone whose levels peak in the luteal phase and during pregnancy, promotes tissue remodeling through matrix metalloproteinase (MMP) activation, which degrades collagen fibers and further increases joint laxity. Parker et al. (2024) [13] systematically reviewed the evidence and confirmed that elevated relaxin levels are associated with increased hip and knee laxity in female athletes. This hormonal influence creates a particularly dangerous biochemical environment during phases when both estrogen and relaxin are elevated, as the combined effect on ligament integrity is greater than the sum of its parts.

3.3. Menstrual Cycle Phases and Knee Laxity

The menstrual cycle can be broadly divided into the follicular phase (days 1–13, culminating in ovulation) and the luteal phase (days 15–28). The pre-ovulatory period, characterized by a sharp LH surge and peak estrogen levels, is consistently identified as the period of greatest joint laxity in research literature [10,16,18].

Maruyama et al. (2021) [10] measured anterior knee laxity across the entire menstrual cycle and confirmed a statistically significant increase during the pre-ovulatory phase. A subsequent study (2022) by the same group [16] found that this effect is most pronounced in eumenorrheic women (those with regular cycles), while oligomenorrheic athletes, despite having chronically altered hormonal profiles, demonstrate less dramatic fluctuations in laxity but may be at risk for other reasons. Shagawa et al. (2021) [18] went a step further, demonstrating that while anterior knee laxity specifically may not always show statistically significant changes, broader joint laxity parameters — particularly genu recurvatum (knee hyperextension) — increase significantly during the ovulatory phase, confirming that the risk assessment must extend beyond a single isolated measurement.

3.4. Oral Contraceptives and ACL Injury Risk

3.4.1. Rationale and Current Evidence

The use of oral contraceptives (OCPs) in female athletes presents a paradox. By suppressing the natural hormonal cycle and maintaining stable, low levels of estrogen and progesterone, OCPs theoretically eliminate the cyclical fluctuations in joint laxity described above. Some earlier studies did suggest a protective effect [2]. However, more recent and methodologically rigorous research paints a considerably more nuanced picture.

Herzog et al. (2020) [2] conducted a large-scale epidemiological study and found that after controlling for selection bias and confounding lifestyle variables, OCP use was not associated with a statistically significant reduction in ACL tear rates. This finding challenges the simplistic narrative that hormonal stabilization translates directly into injury prevention. Furthermore, the work of Lee and Petrofsky (2015) [21] showed a potentially detrimental effect: OCP users exhibited greater ligament damage following heavy exercise and significantly higher post-exercise muscle pain. When OCPs artificially suppress estrogen and make the ACL too stiff, the ligament may lose its shock-absorbing capabilities, acting more like a rigid structure prone to rupture under high stress.

This potential deficit in active stabilization is further supported by neurological observations. Research by Casey et al. (2016) [8] investigating spinal excitability (measured via the H-reflex) didn't catch any statistically important differences between women using OCPs and the naturally menstruating ones nor between different phases of the menstrual cycle in both groups. It can be interpreted from two perspectives; on one side, this indicates that acute, natural hormonal spikes do not disrupt the fundamental neuromuscular control, which may be calming. However, it also further discredits the protective benefits of oral contraceptives; if the spinal reflexes remain unaltered, while the "hardware" part of female body is more susceptible to injuries during the follicular and ovulatory phases of the menstrual cycle, the body fails to neurologically compensate for this vulnerability.

A further study conducted on fifty physically active college females [3] brings some more surprising findings. The authors noticed that during the early follicular phase female athletes have a clear drop in their maximal neuromuscular strength, which naturally makes them more prone to injuries, however this drop in strength happened no matter if the women were on the pill or had a natural cycle.

3.4.2. The Limitations of Using OCPs

The collected evidence suggests that OCPs are not a definitive guarantee for reducing ACL injury risk. Although older studies suggested a protective effect, recent analyses show that those past findings were likely skewed by selection bias. When appropriately controlling for lifestyle and other variables, taking OCPs doesn't seem to show a real reduction in ACL tear rates anymore [2]. Furthermore, functional deficits may not be exclusively caused by sex hormone fluctuations. Instead, diminished muscle performance and lower torque could result from other physiological processes occurring during menstruation, such as blood loss and temporary drops in iron levels. This serves as a crucial reminder that while the pill can effectively stabilize passive ligament laxity, it does not resolve all underlying motor control or functional issues. Ultimately, utilizing oral contraceptives as an injury prevention strategy carries significant consequences that extend far beyond the musculoskeletal system. Therefore, any decision to implement OCPs requires a meticulous cost-benefit analysis and a highly individualized approach.

3.5. Injury Consequences and Rehabilitation Gaps

Female athletes returning to sport after anterior cruciate ligament surgery face a risk of re-injury higher than the uninjured women. Women who have undergone ACL reconstruction maintain significantly higher serum relaxin levels compared to their healthy peers [4]. This persistently elevated level of the tissue-relaxing hormone can create an unfavorable biochemical environment (significantly higher dynamic knee valgus) that predisposes them to subsequent knee injuries. This altered environment is further complicated by the fact that the reconstructed graft does not respond to cyclical hormonal fluctuations in the same way a native ligament does. The biomechanical profile of the knee completely shifts after surgery. Contrary to a healthy joint, the anterior knee laxity in the reconstructed limb decreases during the ovulatory phase and the angle of maximum knee hyperextension no longer fluctuates significantly across the menstrual cycle [20]. This altered structural behavior creates a permanent biomechanical mismatch between the operated and healthy limb throughout the month.

Altered movement mechanics and a different biochemical environment in the knee after an ACL injury can also accelerate degenerative processes. Persistent dynamic knee valgus combined with elevated relaxin levels lead to an abnormal distribution of forces within the joint [4]. This phenomenon may explain why women who have had ligament reconstruction face a much higher risk of developing early-onset knee osteoarthritis.

4. DISCUSSION

When trying to synthesize the mixed findings in current research, a lot of the confusion probably comes down to both what exactly researchers decided to measure and how they did it. The paper by Shagawa et al. (2021) [18] perfectly illustrates the first issue: if they had only checked anterior knee laxity, they would have concluded that the ovulatory hormone spike does not impair joint stability. However, they have also tested other parameters and caught a significant increase in knee hyperextension and general joint laxity, proving that overall injury risk cannot be assessed by checking just one single ligament. Beyond the choice of parameters, discrepancies are also strongly tied to the measurement tool sensitivity. For instance, Shafiei et al. (2016) [7] evaluated joint laxity using standard, manual clinical tests (such as the Lachman and anterior drawer tests) and reported no significant differences across cycle phases. It is likely that manual orthopedic examinations may not be precise enough to detect the subtle, millimeter-scale changes in tissue stiffness induced by estrogen fluctuations. Ultimately, this highlights that relying on isolated ligament tests or basic manual examinations may be insufficient, emphasizing the necessity of using advanced, objective biomechanical equipment so that the tests imitate the real-life conditions in future research.

Despite differing views, current research seems to have come to an agreement that the most dangerous phases from ACL perspective are the late follicular and ovulatory phases. During this period, the knee loses both its passive and active protection; ligament laxity and knee hyperextension significantly increase at that time [16,18]. What is more, muscle strength and functional performance tend to be the worst then as well [1,3,6,11]. This simultaneous failure of both stabilizing mechanisms makes the pre-ovulatory and ovulatory phases the period of highest risk for non-contact knee injuries.

From a methodological perspective, one of the main limitations in the current literature is the tendency to oversimplify the complex relationship between the menstrual cycle and injury risk [5]. Contemporary research often focuses on finding a simple, causal relationship between estrogen levels and musculoskeletal injuries, ignoring the multidimensional nature of this phenomenon. To fully understand physiological responses and develop effective prevention methods, future studies must adopt an interdisciplinary approach. This requires the simultaneous consideration and analysis of multiple variables, such as postural stability, tissue mechanical properties, neurophysiological abilities and the psychological state of the athletes.

Given the highly complex nature of these injuries, detailed screening for each athlete may be of great use. Relying only on standard strength and conditioning tests with simple questionnaires may not be sufficient. Effective screening protocols must incorporate this multidimensional approach by tracking menstrual history, the use of oral contraceptives, specific anatomical traits (such as genu recurvatum) and psychological stress levels [10,12]. When assessing this menstrual history, it is crucial to look beyond just identifying the current cycle phase and evaluate the overall regularity of the athlete's periods [16]. Identifying these complex, individual risk profiles — including chronic hormonal disturbances — allows medical and coaching staff to design targeted interventions, effectively mitigating the risk before the athlete even steps onto the field.

A key issue in contemporary sports physiology and medicine remains the significant underrepresentation of women as research participants. This situation largely stems from researchers' belief that natural fluctuations in sex hormones create difficult-to-control experimental conditions, thereby increasing research costs and reducing statistical power. This clear scientific disparity has severe ethical and practical consequences — it not only drastically limits our understanding of female-specific exercise physiology but also poses a real threat to the health of female athletes. Basing training and injury prevention programs on biomechanical assumptions derived primarily from male-centric studies leaves women systematically exposed to a higher risk of injury and leaves them with fewer opportunities for optimal athletic development.

5. CONCLUSIONS

Current research shows that female athletes face the highest risk of ACL injuries during the late follicular and ovulatory phases. This vulnerability occurs as two main protective systems seem to deteriorate at that exact period: the joints naturally become looser and active muscle control worsens. While oral contraceptive pills can help reduce this ligament laxity, they do not fix the underlying muscle control issues and can cause systemic side effects, which doesn't make them a guaranteed solution. Because of this, any decision to use hormonal birth control for injury prevention requires a careful, individualized cost-benefit analysis. To truly protect female athletes, future prevention strategies should adopt a multidimensional approach that looks at each athlete individually, combining their detailed menstrual history, specific anatomical traits, and objective biomechanical screening.

DISCLOSURE

Author Contributions

Conceptualization was done by Iga Woźniakowska; methodology by Iga Woźniakowska and Aleksandra Misarko; checking by Bartosz Olszewski; formal analysis by Weronika Lech; investigation by Monika Jedwabnik; resources by Stanisław Ścigała and Krzysztof Peszuk; data curation by Adrianna Dobrosielska; writing — rough preparation by Krzysztof Peszuk; writing — review and editing by Hoang Viet Krajewski; supervision by Adrianna Dobrosielska; project administration by Bartosz Olszewski. All authors have read and agreed with the published version of the manuscript.

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The authors report that there is no conflict of interest.

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