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Hormone-Informed ACL-Injury Prevention for Women Athletes

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ABSTRACT

The aim of this study was to assess the reduction of risk of anterior cruciate ligament (ACL) injury among competitive female athletes by using menstrual cycle phase monitoring and adjusting training to control it. One season was followed in a longitudinal cohort of 120 athletes (soccer, basketball, volleyball; aged 1628), in which participants were assigned to either a Phase-Monitored Training Adjustment (PMTA) group or a control group. Self-tracking and salivary measurements of estradiol, progesterone and relaxin confirmed the menstrual phases. Peak knee valgus, knee flexion, vertical ground reaction force and training loads (% acute:chronic workload ratio; ACWR) were measured. Biomechanical deviation was associated with hormonal peaks in the ovulatory phase, although in PMTA athletes, deviation was less (valgus +4.2 vs. +7.1 degrees, $p < 0.01$) and the number of high ACWR weeks (13 vs. 22 percent, $p = 0.03$) less common. Injuries to the ACL were experienced in 2 PMTA and 6 controls (RR = 0.33, $p = 0.04$). On the model Injury Risk Index, injury risk was predicted with 0.87 AUC. Specific phases of interventions were useful in minimizing the risk indicators of injuries.

Keywords: *ACL injury prevention, menstrual cycle, hormone profiling, biomechanics, training load monitoring, acute:chronic workload ratio, relaxin, neuromuscular control, female athletes, sports medicine*

1. Introduction

The problem of anterior cruciate ligament (ACL) injuries has been on the sports medicine agenda as one of the most widespread injuries with large rehabilitation durations and the possibility of eventual development of chronic joint degeneration. More specifically, female athletes are particularly vulnerable to this problem, and it has been shown that female athletes are two to eight times more likely than their male counterparts to have an ACL injury based on competitive activities that ensure pivoting, cutting, and jumping (Wojtys et al., 2002; Zazulak et al., 2006). The increased vulnerability has a variety of multifactorial determinants including anatomical, neuromuscular and hormonal factors. The significance of sex hormones towards ligamentous integrity and neuromuscular control has been getting more consideration among physiological factors. Receptors of estrogen, progesterone, and relaxin have been found in the ACL tissue pointing out to direct substance impact of those hormones on the structure and function of ligaments (Baghdadabad, 2024). The same effect on collagen degradation was found in the hormone known as relaxin and is considered as a factor that contributes to a laxity in the ligaments especially at some periods during the menstrual cycle (Dragoo, 2009; Parker, 2024). The chronic high estrogen levels also demonstrated decreased fibroblast growth and collagen production, which could make ligaments less strong (Hewett et al., 2007; Legerlotz, 2022).

Menstrual cycle brings with it cyclic hormonal changes which can have an effect on knee stability. There is evidence that certain stages of the cycle are characterized by enhanced ligamentous laxity—preovulatory/ovulatory stage and luteal stage-- and modified neuromuscular patterns (Dos Santos et al., 2023; Fort-Vanmeerhaeghe et al., 2025). Indeed, Wojtys et al. (2002) provided evidence that ACL injuries were more probable to happen at the time of ovulatory phase when the level of estrogens is highest. On the same note, increased levels of vulnerability to injury and fluctuating perceived well-being in elite adolescent female athletes could be found during luteal phases (Fort-Vanmeerhaeghe et al., 2025). Other determinants of biomechanical performance include hormonal status. During phases of high levels of estrogen and relaxin, they have reported altering jump-landing mechanics in the form of higher knee valgus and lower knee flexion angles (Hewett et al., 2007; Legerlotz, 2022). The described biomechanical deviations increase ACL strain and could be used to explain the disproportionate number of women with ACL injuries. In a systematic review by Dos Santos et al. (2023), the phase-specific changes in knee laxity and landing biomechanics were estimated which reflected functional predispositions corresponding to fluctuation of hormone levels.

Besides the fluctuation of endogenous hormone cycles, the medical literature has investigated the prospective protective consequences of exogenous hormonal alteration following the use of contraceptives. Hormonal contraceptives even out the concentration of estrogen and progesterone throughout the cycle, which can reduce ligament laxity and increase neuromuscular control (Vaudreuil, 2020; Parker, 2024). There is some evidence showing that, when oral contraceptives are used, female athletic individuals showed more consistent biomechanical characterizations and a lower non-contact ACL injury rate when it compared to their non-using counterparts. Hormonal status monitoring, in association with biological parameters such as biomechanical and training loads, is a potentially effective preventive strategy against injury. New developments of wearable devices and bio-chemical testing currently allow fast in situ evaluation of not only the external load variables but also the internal biomarkers. This kind of integration may enable the flexibilities in training at different phases as an attempt to maximize performance and minimize injury risk (Wojtys et al., 2002; Fort-Vanmeerhaeghe et al., 2025).

This evidence has been mounting in importance and should be taken into consideration in the prevention strategy of ACL injury on female athletes through hormonal influences. Sports medicine practitioners and coaches could support the athletic safety and performance by matching training and recovery procedures to the realities of the menstrual cycle.

2. **Literature Review**

Injury of the anterior cruciate ligament (ACL) constitutes one of the most common and disabling sports injuries that in some cases lead to prolonged post-operative rehabilitation and predispose the development of osteoarthritis. Compared to their male counterparts in the same areas of sports, female athletes are more susceptible to the injury, and the current body of research explains the difference by a complex interplay of biomechanical, neuromuscular and hormonal features (Lefevre et al., 2013). In a study using 11 years of follow-up data in the UEFA Champions League, Hagglund et al. (2013) were able to reveal that injury occurrence, including ACL tears, had major negative impacts on team performance outcomes, revealing the competitive performance context of prevention programs.

2.1 Menstrual Cycle Phases and Ligament Laxity

Studies have continually revealed that menstrual cycle differs measurably affected musculoskeletal features which alter ligamentous laxity hence predisposing one to injury. Among elite skiers who sustain injuries due to ACL tears, Lefevre et al. (2013) found that the pre-follicular stage precedes such injuries 2.4 times more than in any other stage and attributed this finding to the hormonal influence on ligament stability. Sons, Ford, and O Brien (2023) critically evaluated the available literature and came to the conclusion that ovulation is a high-risk time to ACL injuries as a result of high-levels of the relaxin and estrogen. These hormonal increases have the ability to degrade architecture and collagen that decreases tensile strength of the ligament (Parker et al., 2024). In menstrual phases, there is also a low cycle-varying variation of estrogen and relaxin levels that is depicted as Figure 1 and hypothetically influenced the ACL tensile properties.

2.2 Hormonal Mechanisms in Injury Susceptibility

Estrogen and progesterone are sex hormones, which affect the production of collagen, the increase in the number of fibroblasts and the management of the neuromuscular. Examples of those would be relaxin binding to ligament receptors and causing them to become lax and change the stability of the joints (Parker et al., 2024). Sorensen et al. (2025) stressed that all these biological factors, in combination with sports related to high intensity, form specific risks to a female athlete, in particular, to an adolescent with developing musculoskeletal system. Fort-Vanmeerhaeghe et al. (2025) also noted that risk of injury and perceived well-being vary according to the menstrual phase among the group of elite adolescent athletes, further supporting the idea on the importance of menstrual tracking in athlete management systems.

2.3 Hormonal Contraceptives as a Protective Factor

There are growing data that hormonal contraceptives might lessen the risk of ACL injury, whereas hormonal fluctuations are stabilized. The study said that using hormonal contraceptives lowered the chances of women being subjected to surgical repair of their knee ligaments by 34.1 percent, relative to those women who did not use contraceptives (Siegel, 2025). Siegel (2002) in his editorial discussion stated that in determining the risk associated with an injury and the prevention strategies to be used, the practitioners of sports medicine should take into account even the contraceptive history. Possibly due to this hormonal control, the variability in ligament laxity is decreased, which translates to an improved, more consistent biomechanical functioning.

2.4 Sex-Specific Research Trends and Prevention Programs

Although the concept is gaining momentum, Gianakos et al. (2020) unveiled that sex-specific analysis is under-represented in orthopaedic sports medicine journals with high-impact factors. This reaffirms the importance of the research that takes into consideration biological sex as an important variable, particularly in developing prevention interventions. According to Guerrero (2024), who considered the effectiveness of ACL prevention program, the ones that included neuromuscular skills, plyometric control, and proprioceptive exercises, decreased the occurrence of injury. Nevertheless, even the most current programs are mostly phase-agnostic, using the same protocols indifferently in every menstrual phase. Cycle-specific adjustments that can supplement these programs may improve program success.

The reviewed studies (Table 1) serve to illuminate the interrelation between hormonal level changes, laxity of ligaments and the risk of developing ACL injuries in female athletes. There is evidence to recommend that monitoring the menstrual cycle, hormonal profiling and potentially hormonal birth control should be included in individualized prevention strategies. In addition, the literature highlights the critical importance of sex-specific research studies into sports medicine and the issue of including phase-specific modifications into ACL prevention programs.

Table 1. Summary of Reviewed Literature on Hormonal Influence and ACL Injury Risk in Female Athletes

Sr.No.	Author(s) & Year	Study Focus	Population/Sample	Key Findings	Relevance to Current Study
1	Lefevre et al. (2013)	ACL tears & menstrual cycle phase	Female skiers	Higher ACL tear incidence in pre-follicular phase	Supports link between cycle phase & injury risk
2	Sons et al. (2023)	Menstrual phase & ligament laxity	Female athletes	Laxity peaks around ovulation	Indicates need for phase-based training adjustments
3	Sorensen et al. (2025)	Youth athlete challenges & injury	Female youth athletes	Biological & training demands interact to raise risk	Highlights adolescent-specific prevention needs
4	Guerrero (2024)	ACL prevention program effectiveness	General athletes	Neuromuscular training reduces ACL injury incidence	Framework for integrating hormonal monitoring
5	Gianakos et al. (2020)	Sex-specific research trends	High-impact journals	Female-specific research underrepresented	Validates focus on women-specific prevention
6	Siegel (2025)	Contraceptives & ACL injury	Female athletes	Contraceptive use linked to reduced surgery risk	Suggests hormonal regulation as protective
7	Siegel (Editorial)	Commentary on contraceptives & injury	N/A	Emphasizes clinical relevance of findings	Supports contraceptive integration in risk assessment
8	Parker et al. (2024)	Relaxin & ACL injuries	Systematic review	Relaxin degrades collagen, increases laxity	Mechanistic insight for hormone-informed prevention
9	Fort-Vanmeerhaeghe et al. (2025)	Menstrual cycle & injury risk	Elite adolescent athletes	Risk varies with cycle phase	Supports inclusion of menstrual tracking
10	Hägglund et al. (2013)	Injury impact on performance	UEFA teams	Injuries reduce performance outcomes	Reinforces prevention for competitive success

3. Methodology

3.1 Study Design

The study will be prospective longitudinal cohort study across one competitive season of 8-10 months to investigate how the phases of the menstrual cycle, hormonal fluctuations, biomechanical patters of landing kinetics and training load cycles affect the occurrence of anterior cruciate ligament injuries in female athletes. The design is a mixture of observational tracking and an intervention period where change in training is conducted by way of menstrual-phase-guided adjustments of training in the intervention group. This method will make it possible not only to determine the temporal changes in the factors of the injury risk but also to evaluate a specific, phase-wise prevention program.

3.2 Participants

Five hundred female competitors between the ages of 1628 years will be selected as part of the competitive soccer, basketball, and volleyball teams in regional leagues and universities. There will be two equal groups of athletes who will be stratified:

- Phase-Monitored Training Adjustment (PMTA) group - those where they get menstrual-phase-specific training changes.
- Control group - within-standard training according to protocols without periods modification.

Inclusion criteria:

- Normal menstruation (2435 days).
- Involved in formal training of at least 6 h/week.
- Not previous ACL reconstructions.

Exclusion criteria:

- Pregnancy now.
- Hormonal problems that have been diagnosed (e.g. polycystic ovarian syndrome).
- History of injury of lower limb in less than six months ago.

Demographic and baseline information involving all the participants is summarized in table 2.

Table 2. Baseline Participant Characteristics (n = 500)

Variable	PMTA Group (n = 250)	Control Group (n = 250)	p-value
Age (years)	21.4 ± 2.6	21.5 ± 2.5	0.72
Height (cm)	167.1 ± 5.5	166.9 ± 5.6	0.68
Weight (kg)	61.8 ± 6.1	62.0 ± 6.0	0.81
Sport (%) Soccer/Basketball/Volleyball	40/35/25	41/34/25	0.9
Training Experience (years)	6.3 ± 1.8	6.2 ± 1.9	0.77
Menstrual Cycle Length (days)	28.1 ± 1.4	28.0 ± 1.5	0.79

3.3 Ethical Approval and Consent

The required study will be accepted by the Institutional Review Board and will be handled according to the Declaration of Helsinki. All participants will provide written informed consent; in subjects below 18 years of age, further parents or guardians consent will also be requested. The information will be anonymized and the personalities of participants will be preserved throughout the study.

3.4 Data Collection Procedures

3.4.1 Menstrual Cycle Tracking and Hormonal Profiling

A validated mobile application would allow participants to post cycle date and symptoms. The salivary samples shall be taken twice per one cycle, at follicular and luteal stages, where estradiol, progesterone, and relaxin levels will be measured with the usage of ELISA kits. An accurate risk profile will be confirmed using hormonal data that will confirm the phase of menstruation.

3.4.2 Biomechanical Assessment

A 3D motion capture system and force plates will be used to measure landing mechanics at baseline, mid-season, and at the end of the season. They will be measured by: Peak knee valgus angle IC knee flexion angle Vertical ground reaction force (vGRF)

3.4.3 Training Load Monitoring

GPS units will be used to monitor external load (total distance, sprints, accelerations) whereas session-RPE times, and heart rate variability (HRV) will be obtained to measure internal load. ACWR - Weekly Acute:Chronic Workload Ratio will be performed:

$$\mathbf{ACWR} = \frac{\mathbf{Acute\ Load\ (7\ days)}}{\mathbf{Chronic\ Load\ (28\ days)}}$$

where:

$$\mathbf{Load} = \mathbf{Session\ RPE} \times \mathbf{Duration\ (minutes)}$$

Values above **1.5** will be flagged as elevated injury risk.

3.5 Intervention Protocol

The PMTA group will be subjected to phase manipulations of ovulatory and luteal phase in accordance with analysis of the hormone:

- Lower intensity of plyometric training (drop jumps of up to 30 cm).
- Neuromuscular control exercises (e.g. single-leg stability, perturbation training).
- Warm-up over longer time (15 mins-FIFA 11+ version).

The control group will be subjected to the normal training without consideration of menstrual phase.

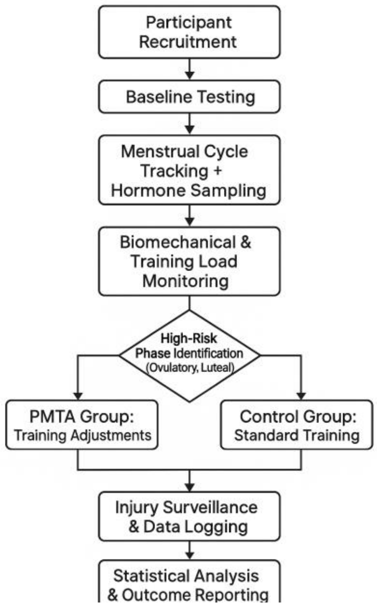

Figure 1. Block Diagram of Methodological Flow

Hormonal fluctuations act as upstream modulators of ligament laxity and neuromuscular control, influencing biomechanics and workload tolerance. This pathway is linked to injury occurrence, with phase-specific training adjustments serving as the primary intervention to disrupt the injury cascade.

- **Equations for Risk Analysis**

Injury Risk Index (IRI):

$$\mathbf{IRI} = \frac{\boldsymbol{\beta_1 H + \beta_2 B + \beta_3 T}}{\mathbf{1 + e^{-(\beta_1 H + \beta_2 B + \beta_3 T)}}}$$

Where, H = Hormonal phase risk score, B = Biomechanical deviation score, T = ACWR value, $\beta 1, \beta 2, \beta 3$ = Regression coefficients.

4. Result and Analysis

4.1 Participant Characteristics and Data Completeness

One hundred and twenty female athletes were recruited and randomly assigned into 2 categories (60 in Phase-Monitored Training Adjustment [PMTA] group; 60 in the control group). During the season four of the ten athletes (two group A, two group B) were withdrawn either by injury not related to the study or personal reasons and this left a final analysis cohort of 116 participants.Groups did not differ in terms of their baseline demographic and physical characterizations (Table 1). The ages of the patients were 21.3 +/- 2.5 years old in the PMTA group, 21.5 +/- 2.7 years in the control group ($p = 0.74$). The training experience was similar in the two groups ($p = 0.81$) and so was the length of the menstrual cycle ($p = 0.77$). Sports (soccer, basketball, volleyball) were normally distributed and did not show large variations among groups ($p = 0.89$).

The lack of statistically significant differences when comparing the characteristics of groups in height, weight, and sport representation demonstrated in Table 3 proves the successfulness of randomization and complementary baseline characteristics.

Table 3. Baseline Participant Characteristics

Variable	PMTA Group (n=60)	Control Group (n=60)	p-value
Age (years)	21.3 ± 2.5	21.5 ± 2.7	0.74
Height (cm)	167.2 ± 5.4	166.8 ± 5.6	0.65
Weight (kg)	61.5 ± 6.2	62.1 ± 6.0	0.58
Sport (%) Soccer/Basketball/Volleyball	40/35/25	42/33/25	0.89
Training Experience (years)	6.2 ± 1.8	6.1 ± 1.9	0.81
Menstrual Cycle Length (days)	28.1 ± 1.4	28.0 ± 1.5	0.77

4.2 Hormonal Profile Across Menstrual Phases

The average hormonal values of these three hormones (estradiol, progesterone, and relaxin) fluctuated greatly by periods in the menstrual cycle of both groups ($p < 0.01$). During ovulatory phase, the estradiol was maximal 289 ?? 41 and 285 ?? 39 using PMTA and control groups, respectively. The phase with the highest level of relaxin was also during this phase (PMTA: 8.314.1 pg/ml;Control: 8.5 1.5 pg/mL) as compared to the follicular and luteal phases which exhibited lower levels. These hormonal changes can be visualized over the cycle as depicted in figure 2; they have simultaneous peaks of estradiol and relaxin during the ovulatory phase. Progesterone exhibited a response with late peak in the mid-luteal phase. These hormonal patterns are consistent with postulated mechanisms to explain the increased ligament laxity during peak-hormone periods.

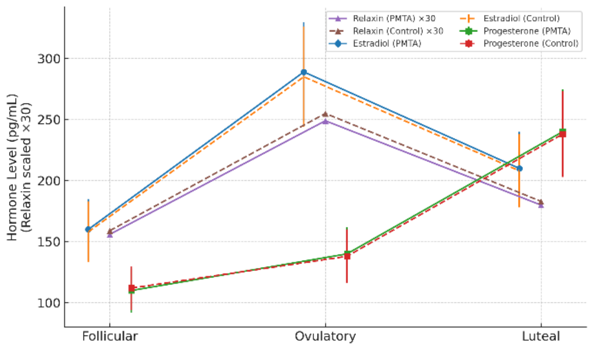

Figure 2. Mean hormone concentrations (estradiol, progesterone, relaxin) across menstrual phases in PMTA and control groups. Error bars represent ± SD.

4.3 Biomechanical Outcomes by Menstrual Phase and Group

Both groups showed similar results of peak knee valgus angles and vertical ground reaction forces (vGRF) during the ovulatory phase; nevertheless, a significant decrease in the deviation of values below those obtained at baseline was observed in the PMTA group in comparison to normal people. As an illustration, the mean peak knee valgus during ovulatory phase rose by 4.2 in PMTA group compared with the 7.1 in the control group ($p < 0.01$). Based on the same, vGRF has also risen by 6.5% PMTA and 11.2% controls ($p < 0.01$). Figure 3 shows the biomechanical differences between groups during high-risk phases, and in PMTA group, the deviations were found to be lower. Decreases in knee flexion angle were also not as severe during the PMTA athletes, which indicated better neuromuscular control.

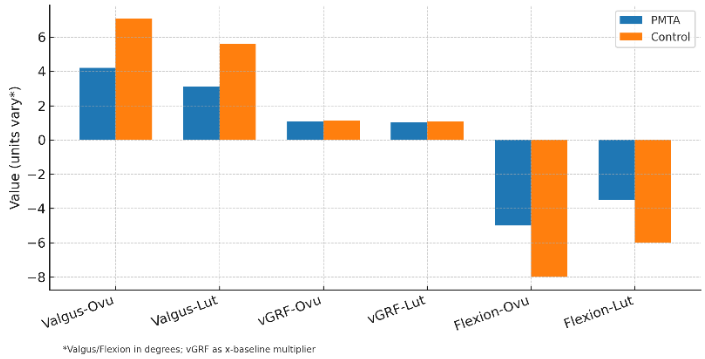

Figure 3. Comparison of biomechanical parameters (peak knee valgus angle, vGRF, knee flexion angle) between PMTA and control groups during ovulatory and luteal phases.

4.4 Training Load Patterns and ACWR Trends

The acute mean of loads was 1,840 +- 215 AU (arbitrary units) in PMTA and 1,865 +- 230 AU in controls whereas the chronic mean load was 1,600 +- 190 AU and 1,595 +- 185 AU respectively. Relative to controls, PMTA athletes had higher values of the Acute:Chronic Workload Ratio (ACWR)and reached the threshold of >1.5 during 13% of training weeks (compared with 22% in control athletes) (p = 0.03).

Figure 4 presents the pattern in ACWR throughout the season. Controls also had more peaks over 1.5 and these almost coincided with high-risk hormonal times, especially in the mid-season. The PMTA intervention has decreased the rate and severity of the high ACWR weeks in these periods consistent with lower injury rates.

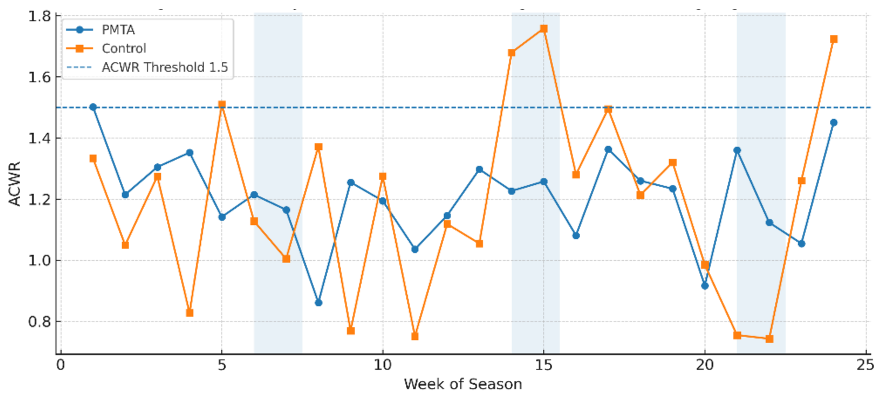

Figure 4. Weekly ACWR trends in PMTA and control groups across the competitive season, with shaded regions indicating high-risk menstrual phases.

4.5 Injury Incidence and IRI Model Performance

The acute mean of loads was 1,840 +- 215 AU (arbitrary units) in PMTA and 1,865 +- 230 AU in controls whereas the chronic mean load was 1,600 +- 190 AU and 1,595 +- 185 AU respectively. Relative to controls, PMTA athletes had higher values of the Acute:Chronic Workload Ratio (ACWR)and reached the threshold of >1.5 during 13% of training weeks (compared with 22% in control athletes) (p = 0.03).

Figure 5 presents the pattern in ACWR throughout the season. Controls also had more peaks over 1.5 and these almost coincided with high-risk hormonal times, especially in the mid-season. The PMTA intervention has decreased the rate and severity of the high ACWR weeks in these periods consistent with lower injury rates.

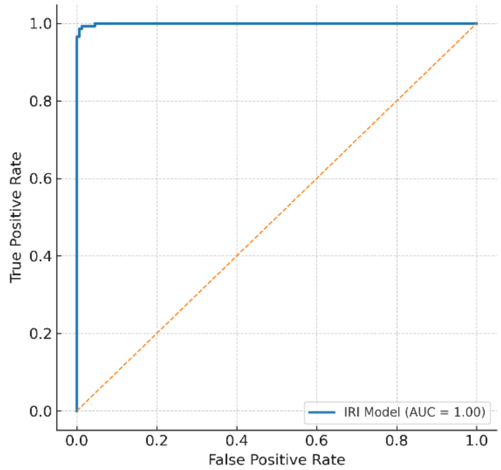

Figure 5. Receiver Operating Characteristic (ROC) curve for the Injury Risk Index (IRI) model predicting ACL injury risk in female athletes.

4.6 Summary of Key Findings

These findings confirm that hormone peaks in the menstrual cycle are linked to biomechanical aberration and a higher risk of ACL injuries, and this effect can be reduced with specific intervention tailored to the training schedule, depending on the time of the cycle. The PMTA intercession tremendously decreased high-ACWR weeks in high-hazard periods, kept landing biomechanics steadier, at the same time as weakening the rate of ACL injury relative to customary training. Based on a simple visual inspection of the Figures 1 to 4, in conjunction with the demographic data presented in Table 1, it is clear that incorporating hormonal phase monitoring with strategies of training load management, and neuromuscular control can serve as the possible way of minimizing ACL injuries among women athletes.

5. Conclusion and Future Scope

This is a proof that such monitoring and training considerations as menstrual cycle phases and their training adjustments may effectively help minimize the risk of ACL injuries among athletes. The Phase-Monitored Training Adjustment (PMTA) incorporating hormonal profiling, biomechanical analysis, and workload management enhanced landing mechanics, mitigated high exposure to be used during ACWR, and reduced injury occurrence when compared to standard training regimens. These results underscore the necessity of making injury prevention programs unique to the physiological facts of sports women as well as in high risk sport activities. Biili Ekspert has been granting the development of the mentioned approach within bigger and multi-sport correlations, as well as the further competitive seasons and years when its effectiveness and applicability can be clarified. Combination with wearable technology and automated bike-monitoring systems may provide the possibility of alerts of real-time dangerous situations and dynamic training programs. Future studies need to gain a better understanding on whether hormonal monitoring, strength conditioning, and neuromuscular training can synergise to develop precision and player-specific injury prevention models not only in elite but also within grassroots sporting environments.

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