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A Critical Analysis of the Factors Contributing to Anterior Cruciate Ligament Injuries in Female Athletes

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Abstract

Anterior Cruciate Ligament (ACL) injuries are a prevalent concern in athletic population, particularly among female athletes who are disproportionately affected. The increased incidence of ACL injuries in females is attributed to a combination of anatomical, physiological, and biomechanical factors that influence knee stability. This review comprehensively explores these contributing factors, highlighting gender-specific anatomical differences such as wider pelvis, increased quadriceps (Q) angle, and steeper tibial slopes, all of which predispose females to greater knee valgus during dynamic activities. Furthermore, hormonal influences and greater ligament laxity are discussed as physiological contributors to increased ACL injury risk. Biomechanical factors such as reduced knee flexion, increased knee valgus, and altered muscle activation patterns further amplify the risk of ACL tears in female athletes. Despite extensive research, gaps remain in the understanding of how these factors interact and influence injury susceptibility. This article is focussed on the critical points in the current literature, analyzing key risk factors, and identifying future research directions that can inform more effective prevention strategies. A better understanding of these factors will ultimately contribute to reducing the incidence of ACL injuries among female athletes and improving long-term strength and stability of knee joint.

Keywords: ACL injuries; ACL tear prevention; Anterior Cruciate Ligament; Athletic injury risk; Biomechanical factors; Female athletes; Gender differences in sports injuries; Injury prevention; Knee valgus; Ligament laxity; Q angle; Sports biomechanics

Introduction

ACL injuries are prevalent in sports, particularly in activities involving sudden stops, changes in direction, and pivoting motions. These injuries often occur due to direct trauma, such as a collision or a twisting motion of the knee beyond its normal range of motion. Athletes in sports like football, soccer, basketball, and skiing are at higher risk due to the dynamic nature of these activities [1]. ACL injuries can have significant consequences, including pain, instability of the knee joint, and potential long-term complications like osteoarthritis. Consequently, understanding the mechanisms, risk factors, and management of ACL injuries is crucial for athletes, coaches, and healthcare professionals alike. In elite athletes, the anterior cruciate ligament (ACL) often sustains injuries, with females exhibiting a significantly higher susceptibility—up to eight times more likely—compared to males [2]. Extensive research has delved into biomechanical and hormonal factors,

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yet there are still unidentified variables warranting further exploration. The injury mechanisms exhibit variance between genders, with anatomical distinctions notably amplifying the risk in females [3]. Hormonal influences, both internal and external, influence ACL laxity and might alter the injury risk profile [4].

Despite the advances in understanding the biomechanical and physiological factors contributing to ACL injuries in female athletes, several gaps remain. Current research often focuses on isolated factors without considering the complex interactions between them [5]. For instance, the combined effects of anatomical structure, hormonal influences, and neuromuscular control on ACL injury risk are not fully understood [6]. Additionally, while some preventive training programs have shown promise, their efficacy across diverse populations and sports remains to be fully established [7].

Moreover, much of the existing literature has focused on nonmodifiable risk factors, such as anatomy and physiology, rather than exploring modifiable factors, such as technique and training interventions. This has limited the development of targeted prevention strategies that can be implemented across different levels of athletic participation.

This comprehensive review seeks to synthesize current research on the biomechanical factors contributing to ACL injuries in female athletes. By integrating findings from anatomical, physiological, and biomechanical studies in this article, we provide a holistic understanding of the risk factors and their interactions. Furthermore, we identified existing gaps in the literature and proposed areas for future research. Ultimately, this review aspires to contribute to the development of effective, evidence-based prevention and intervention strategies to reduce the incidence of ACL injuries among female athletes.

Anatomical Factors

Understanding the anatomical factors that predispose women to ACL tears is crucial in developing effective prevention strategies. The disparity in ACL injury rates between male and female athletes has been well-documented, with female athletes being at a significantly higher risk [8]. This section critically reviewed the anatomical differences that contribute to this increased susceptibility.

(i) *Femoral Notch Width:* The femoral notch width is narrower in females compared to males. This anatomical difference has been associated with a higher incidence of ACL injuries in female athletes [9]. A narrow femoral notch may lead to impingement of the ACL during physical activity, increasing the risk of tears [9].

(ii) *Q Angle:* The quadriceps angle (Q angle), which is the angle between the quadriceps muscles and the patella tendon, is generally larger in females [9]. This increased Q angle can lead to greater lateral pull on the patella, contributing to knee instability and higher risk of ACL injuries [10]. Figure 1 depicts the average difference between Q angle in 70 female athletes compared to 154 male athletes [10].

(iii) *Pelvic Structure:* Female athletes typically have a wider pelvis compared to their male counterparts. This anatomical feature can affect the alignment of the femur and tibia, resulting in a valgus knee position (knee collapse inward) during dynamic activities [11]. This valgus positioning increases the strain on the ACL, making it more susceptible to injury [11].

(iv) *Ligament Laxity:* Studies have shown that females generally have greater ligament laxity compared to males. Increased laxity can lead to reduced joint stability, particularly in the knee, which is a critical factor in non-contact ACL injuries [12]. Hormonal influences, particularly the effects of estrogen, are thought to contribute to this increased laxity [13]

(v) *Tibial Slope:* The posterior tibial slope is composed of two parts: the medial tibial slope, which refers to the angle of the medial (inner) side of the tibial plateau, and the lateral tibial slope, which represents the angle of the lateral (outer) side of the tibial plateau, both of which influence knee joint mechanics and ACL injury risk [14]. A steeper tibial slope can result in increased anterior shear forces on the knee, thereby heightening the risk of ACL tears. Figure 1 depicts the posterior tibial slope from 33 female athletes compared to that of 41 male athletes [14].

(vi) *Intercondylar Notch Size:* Females often have a smaller intercondylar notch size, which may contribute to higher ACL injury rates. A smaller notch can limit the space available for the ACL, increasing the likelihood of impingement and subsequent injury during high-stress activities [15].

(vii) *Muscle Strength and Activation Patterns:* Anatomical differences also influence muscle strength and activation patterns. Females typically have a different muscle activation strategy, often relying more on quadriceps muscles rather than hamstrings during dynamic movements [16]. This reliance can increase the anterior shear forces on the knee, further stressing the ACL [16].

Physiological Factors

In addition to anatomical differences, physiological factors play a significant role in predisposing female athletes to ACL injuries. These factors include hormonal fluctuations, neuromuscular control, and other gender-specific characteristics that can influence the stability and function of the knee joint.

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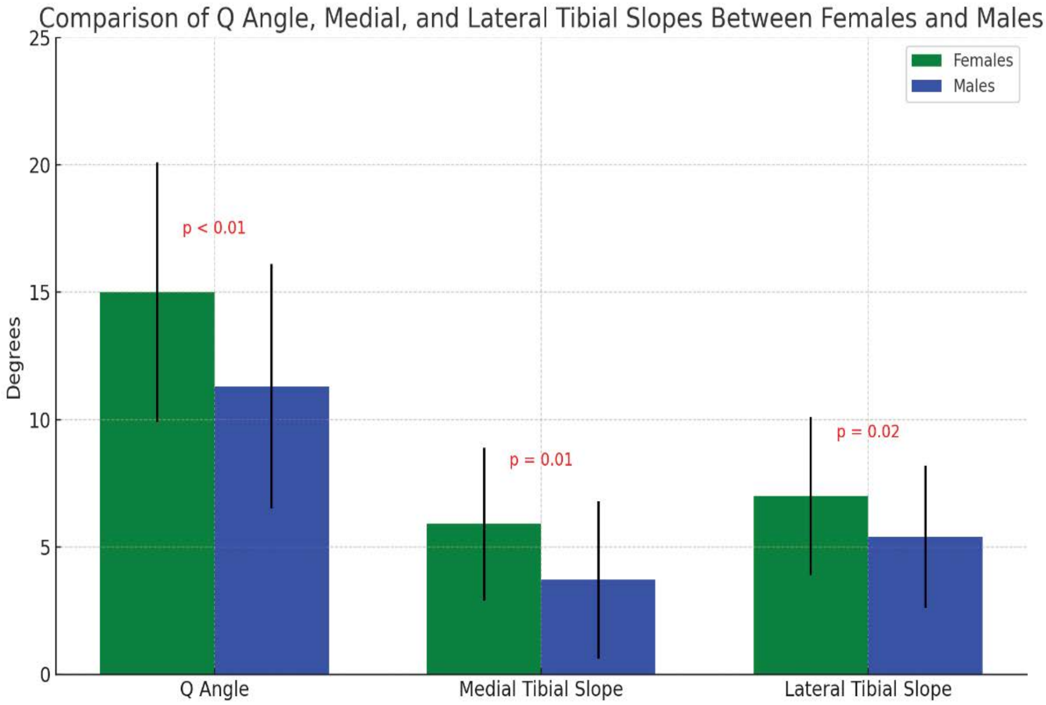

Figure 1: Differences in Q angle (N = 224), medial tibial slope and lateral tibial slope (N=74) between females and males. Values are presented as mean ± SD. Data are compiled from the published findings of Mitani et al. [10] and Hashemi et al. [14]. There is a significant difference in the Q angle, medial tibial slope, and lateral tibial slope between the males and females, as shown with the p values.

(i) Hormonal Fluctuations: Hormonal variations, particularly those involving estrogen and progesterone, are thought to affect the mechanical properties of ligaments. Estrogen, for instance, has been shown to decrease collagen synthesis and increase ligament laxity, potentially weakening the ACL and making it more susceptible to injury [17]. These hormonal effects are particularly pronounced during certain phases of the menstrual cycle, further increasing the risk of injury [18]. As seen in Figure 2, researchers found significant increases in ACL laxity during both the follicular phase ($p = 0.048$) and luteal phase ($p = 0.006$) of the menstrual cycle, indicating that hormonal surges in estrogen and progesterone may contribute to greater ligament laxity, potentially elevating the risk of ACL injury in women during these phases [19].

(ii) Neuromuscular Control: Neuromuscular control, which involves the coordination of muscle activity to stabilize joints, is typically different in female athletes compared to males. Females often exhibit delayed activation of stabilizing muscles, such as the hamstrings, which are crucial for protecting the ACL during dynamic movements [20]. This delay can result in greater anterior tibial translation and increased strain on the ACL [20].

Biomechanical Factors

Biomechanical factors also significantly contribute to the higher incidence of anterior cruciate ligament (ACL) injuries in female athletes. These factors include movement patterns and joint dynamics during physical activities. Understanding these biomechanical differences is crucial for developing effective injury prevention strategies.

(i) *Knee Valgus Angle:* Female athletes often exhibit greater knee valgus (inward collapse of the knee) during dynamic activities such as landing, cutting, and pivoting. This movement pattern places increased stress on the ACL, making it more susceptible to injury [17]. As seen in Figure 3, researchers found that women demonstrated significantly greater knee valgus angles than men during a single leg drop landing, both at initial contact and maximum knee flexion [21].

(ii) *Hip and Knee Kinematics:* During high-risk movements, females tend to have different hip and knee kinematics compared to males. Studies have shown that women often have greater hip internal rotation and adduction, which can lead to increased knee valgus and higher ACL loading [22-23].

(iii) *Landing Mechanics:* Differences in landing mechanics between genders have been identified as a key risk factor. Female athletes typically land with less knee flexion and greater quadriceps activation, which increases the anterior shear force on the tibia, thus placing more stress on the ACL [24-25]. As seen in Figure 4, researchers found that men demonstrated significantly greater knee

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flexion angles than women during both initial contact and maximum flexion in 90° and 135° cutting maneuvers [26].

(iv) *Ground Reaction Forces:* Studies have found that females generate different ground reaction forces during athletic activities. For instance, higher peak vertical ground reaction forces and greater medial ground reaction forces during landing can contribute to increased ACL loading and risk [27-28].

(v) *Dynamic Knee Stability:* Dynamic knee stability, influenced by neuromuscular control, is often compromised in females. Poor neuromuscular control during dynamic activities can result in improper knee alignment and increased ACL strain [29].

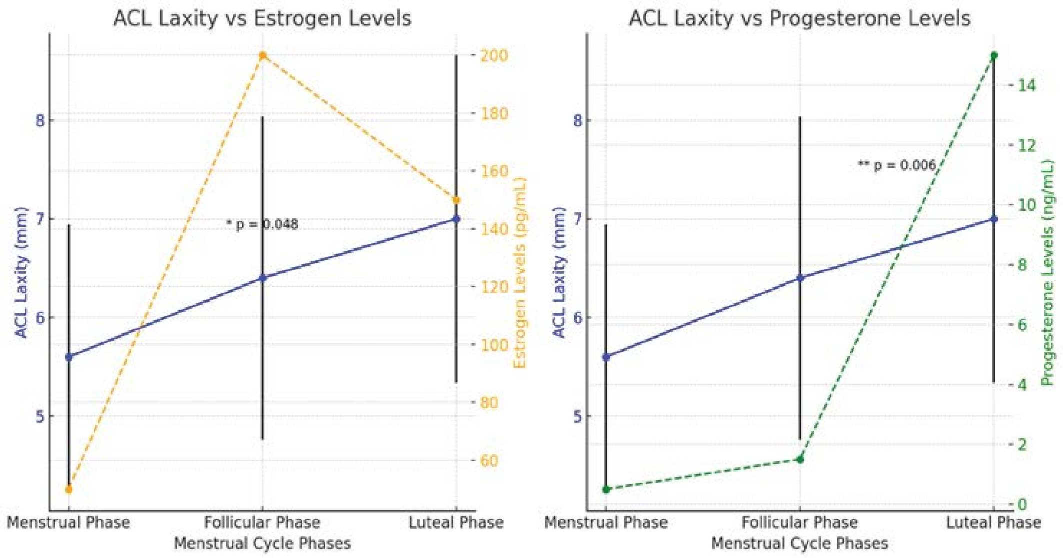

Figure 2: Significant Changes in ACL Laxity During Menstrual Cycle Phases in Relation to Estrogen and Progesterone Levels, (N=7). Values are presented as mean ± SD. Data are compiled from the published findings of Heitz et al. [19]. The level of significant difference between the ACL laxity and estrogen or progesterone levels is shown with the p values.

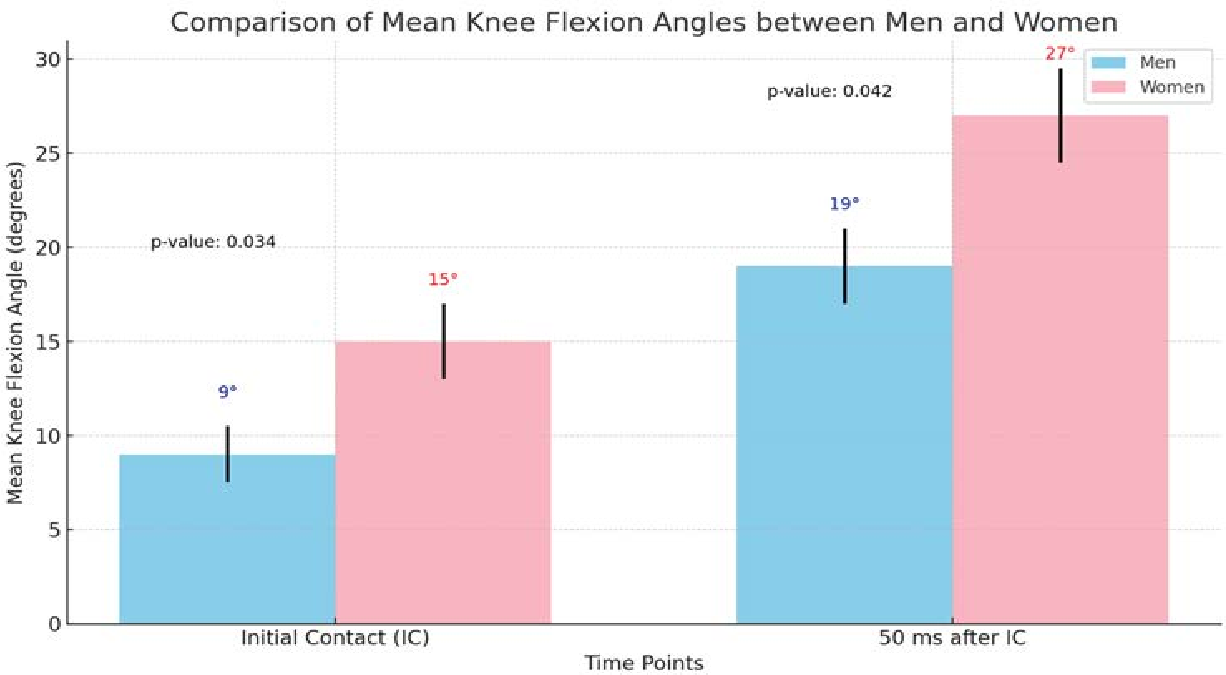

Figure 3: Comparison of Knee Valgus/Varus Angles Between Men and Women During Single-Leg Drop Landing at Initial Contact and Maximum Knee Flexion, (N=32). Values are presented as mean ± SD. Data are compiled from the published report of Russell et al. [21]. The level of significant difference in the knee Valgus/Varus angles between the males and females is shown with the p values.

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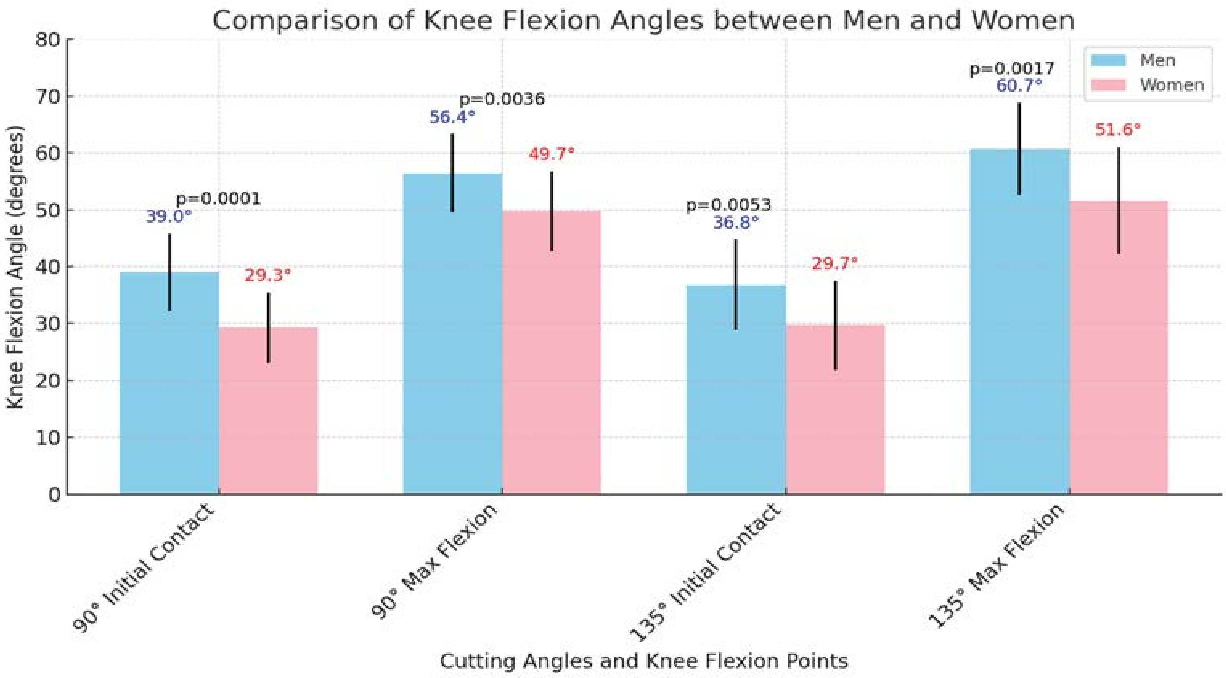

Figure 4: Comparison of Cutting Angles and Knee Flexion Angles Between Men and Women During 90° and 135° Cutting Maneuvers, (N=40). Values are presented as mean ± SD. Data are compiled from the published report of Sheu et al. [26]. The level of significant difference in the knee flexion angles between the males and females is shown with the p values.

Discussion

This comprehensive review has examined the anatomical, physiological, and biomechanical factors contributing to the heightened risk of ACL injuries in female athletes. Anatomically, females tend to have a wider pelvis, increased Q angle, and greater ligament laxity, all of which contribute to knee instability. Physiological factors such as hormonal fluctuations and differences in neuromuscular control further exacerbate this risk. Biomechanically, movement patterns like greater knee valgus and less knee flexion during landing increase the strain on the ACL, making it more susceptible to injury.

The findings of this review underscore the necessity for multifaceted prevention strategies that address the various contributing factors. Effective prevention programs should incorporate neuromuscular training, strength conditioning, and biomechanical training to optimize movement patterns and enhance joint stability. Such programs can significantly reduce the incidence of ACL injuries among female athletes by targeting both modifiable and non-modifiable risk factors.

Recommendations for Future Research

Future research should focus on a more integrative approach that considers the interactions between anatomical, physiological, and biomechanical factors. Longitudinal studies conducting long-term studies to monitor the progression of risk factors and injury incidence over time and tracking athletes over multiple seasons would provide valuable insights into the evolution of injury risk factors. It is critical to develop and test integrated prevention programs that combine neuromuscular, strength, and biomechanical training. Real-world testing is warranted to validate the effectiveness of prevention strategies in real-world athletic contexts. Finally, personalized approaches will create individualized prevention programs tailored to the specific risk profiles of athletes. Overall, development of rigorous testing and comprehensive training programs in real-world sports environment will ensure their effectiveness and applicability.

Practical Applications

Coaches, trainers, and healthcare professionals can integrate the insights from this review into their training regimens. Emphasizing exercises that improve neuromuscular control, promote proper landing mechanics, and strengthen the surrounding musculature will help mitigate ACL injury risks. Educational initiatives to raise awareness about these risk factors and preventive measures are also crucial in protecting female athletes.

Final Thoughts

The multifactorial nature of ACL injuries in female athletes necessitates a comprehensive and collaborative approach to prevention. By addressing the interplay of anatomical, physiological, and biomechanical factors, we can develop effective strategies to safeguard female athletes from these debilitating injuries. Continued research and innovation

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in this field are essential to refine these strategies and promote their widespread adoption in sports programs globally.

Major Key Points and Outstanding Questions

- Female athletes are significantly more prone to ACL injuries due to a combination of anatomical, physiological, and biomechanical factors.
- Factors such as a wider pelvis, steeper tibial slopes, and increased Q angle in females contribute to higher knee valgus and instability, raising the risk of ACL tears.
- Physiological Contributions Hormonal fluctuations and greater ligament laxity in females contribute to increased joint instability, particularly during dynamic sports movements.
- Females often exhibit less knee flexion, greater knee valgus, and altered muscle activation patterns during landing and pivoting maneuvers, which further strain the ACL.
- Despite extensive research, gaps remain in understanding how these factors interact. Effective injury prevention strategies must address both modifiable and non-modifiable risk factors.
- Future studies should focus on developing personalized prevention programs that consider the complex interplay of anatomical, physiological, and biomechanical factors to reduce ACL injury incidence.
- What are the most effective training and prevention strategies to reduce the impact of biomechanical risk factors such as knee valgus and reduced knee flexion in female athletes?
- How can individualized prevention programs be tailored to account for the anatomical and physiological differences between male and female athletes, while also considering sport-specific demands?
- What are the long-term outcomes of ACL injury prevention programs, and how do they affect injury recurrence rates and overall joint health in female athletes?
- How do different playing surfaces and footwear affect the biomechanical and neuromuscular risk factors contributing to ACL injuries in female athletes?

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