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Anterior Cruciate Ligament Injury Pathogenesis, Epidemiology, Diagnosis and Prevention

Baihan Zhang

Suzhou Industrial Park Ulink High School, Suzhou, China
baihanzhang971@gmail.com

Abstract. The anterior cruciate ligament (ACL) is a frequently injured knee structure, causing significant clinical, social and economic burdens due to high incidence, prolonged recovery and long-term sequelae like post-traumatic osteoarthritis. This study explores the ACL injuries' pathophysiology, epidemiology, diagnosis, prevention and rehabilitation. Epidemiologically, the young active populations, especially female athletes and adolescents, are disproportionately affected, with 70–80% of injuries from non-contact mechanisms (e.g., awkward landings). Pathogenically, the risks stem from anatomical, neuromuscular, hormonal and extrinsic (sport, fatigue) factors. Diagnosis uses a multimodal approach: patient history, physical exams (e.g., Lachman test), MRI (the gold standard), and emerging the AI tools. Prevention relies on evidence-based programs (FIFA 11+, PEP) targeting modifiable risks. Rehabilitation follows phase-oriented, criterion-based protocols, integrating physical training and psychological support to reduce 25% re-injury risk. Despite advancements, challenges like osteoarthritis and uneven prevention implementation remain. This study emphasizes personalized interventions and interdisciplinary collaboration to mitigate ACL injury burdens.

Keywords: Anterior cruciate ligament, injury prevention, rehabilitation

1. Introduction

The anterior cruciate ligament (ACL) is one of the most frequently injured knee structures, posing substantial challenges to orthopedic surgeons and sports medicine specialists [1]. As a key stabilizer, it maintains the knee's anterior-posterior and rotational stability, enabling complex movements like cutting, turning, and jumping. ACL injury not only causes acute functional impairment but also leads to long-term consequences, including meniscal damage, chronic instability, and accelerated osteoarthritis [2]. With the global rise in high-intensity sports participation, ACL injuries have become a critical clinical, social, and economic concern.

Epidemiologically, ACL injuries are highly prevalent. In the US alone, 200,000–400,000 ACL ruptures occur annually, with a large proportion requiring surgical reconstruction [3]. Similar trends are observed globally, especially in regions with high youth and professional sports engagement. Demographically, female athletes and adolescents are at higher risk—female athletes face 2–7 times greater injury odds than males in comparable sports—due to interactions between anatomical traits, neuromuscular control, hormonal factors, and sport-specific demands [4].

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ACL injury etiology includes contact and non-contact causes, with 70–80% being non-contact, triggered by dynamic movements like rapid direction changes, deceleration, or poor landing mechanics [5]. Contact injuries, though less common, involve direct trauma and often coincide with damage to other knee structures, complicating diagnosis and treatment [6]. Diagnosis relies on a combination of patient history, physical examination (e.g., Lachman test), and advanced imaging, with MRI as the gold standard for assessing ligament integrity and associated injuries [7]. Recent AI advancements may further enhance diagnostic accuracy and reduce delays [8].

Treatment plans are personalized, considering age, activity level, and patient expectations. Surgical reconstruction is standard for young, active individuals, while conservative care with rehabilitation suits older or less active patients. Prevention programs like the FIFA "11+" have proven effective in lowering injury rates, but re-injury and long-term sequelae remain common. This study explores the pathophysiology, epidemiology, diagnosis, and prevention of ACL injuries, aiming to provide evidence-based solutions to reduce their burden across populations.

2. Pathogenesis of ACL injury

2.1. Anatomical, histological and biomechanical foundations

The ACL plays a pivotal role in knee stability by restricting anterior tibial translation relative to the femur and regulating rotational movements [1]. Its unique anatomical orientation and biomechanical functions expose it to significant stress during daily activities and sports, making it vulnerable to injury [2]. Anatomically, the ACL originates from the posteromedial side of the lateral femoral condyle and inserts anterior to the tibial intercondylar eminence. Its oblique path allows it to resist anterior shear forces and regulate tibial rotation [4]. Histologically, it comprises 90% type I collagen (for tensile strength) and 10% type III collagen (for elasticity), with a limited vascular supply from the middle genicular artery—this poor blood flow, especially in the mid-substance, results in weak intrinsic healing capacity [5,6].

Biomechanically, ACL injuries are categorized as contact or non-contact. Non-contact injuries, the majority, occur via abrupt pivoting, deceleration, or awkward landings, often with the knee in 0–30 degrees of flexion—this position maximizes ACL strain, especially with tibial rotation [8,9]. Strong ground reaction forces and inadequate muscle absorption exacerbate ligament loading. Contact injuries stem from direct knee trauma (e.g., lateral impacts in skiing or football) and frequently cause concurrent damage to the menisci or medial collateral ligament (MCL), forming the "unhappy triad".

2.2. Intrinsic and extrinsic risk factors

Intrinsic factors predispose individuals to ACL injury, with sex-based differences being prominent. Female athletes face a 4–7 times higher risk due to anatomical traits (narrower intercondylar notch, smaller ACL cross-section, larger Q-angle), hormonal fluctuations (estrogen/relaxin-induced ligament laxity), and neuromuscular patterns (quadriceps dominance, delayed hamstring activation) [4,5]. Genetic factors also play a role—variations in collagen-related genes (e.g., COL1A1, COL5A1) are linked to ligament susceptibility [6].

Extrinsic factors include sport-specific demands, playing surfaces, footwear, and fatigue. Sports requiring frequent rotation, cutting, or jumping (basketball, soccer, volleyball) increase risk [8]. Hard surfaces and improper footwear amplify ground reaction forces, while fatigue impairs neuromuscular control, leading to suboptimal landing mechanics [9]. Occupational risks (e.g.,

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construction, military work) and sedentary lifestyles (weakening neuromuscular control) also contribute, as does elevated BMI, which increases knee joint stress [9,10].

2.3. Associated injuries, long-term sequelae and emerging insights

ACL injuries rarely occur in isolation. Shear forces post-injury often cause meniscal tears (especially medial meniscus), while articular cartilage lesions and bone bruises are common on MRI [7]. Even with surgical reconstruction, these concurrent injuries raise risks of chronic instability and post-traumatic osteoarthritis [8]. Recent advancements—including 3D motion capture (identifying high-risk patterns like dynamic valgus collapse), computational biomechanical modeling, and hormonal research—have deepened understanding of injury mechanisms, supporting tailored prevention for high-risk groups like female athletes [9].

3. Epidemiological characteristics and susceptible populations

ACL injuries are a major public health concern due to their high incidence, costly treatment, and long-term impact on musculoskeletal health [1]. Epidemiological studies consistently show they disproportionately affect young, active individuals, particularly those in pivoting and jumping sports [2]. Analyzing incidence trends, demographic distributions, and population-specific risks is critical for developing targeted interventions.

3.1. Global incidence and demographic patterns

Global ACL injury incidence varies by sports participation, healthcare access, and reporting standards. In the US, the incidence is 69 per 100,000 person-years, with 200,000–400,000 annual injuries and one-third requiring surgical reconstruction [4]. Incidence has risen significantly in recent decades, especially among adolescents and young adults, driven by early sport specialization, year-round training, and increased competitive youth sports engagement—for example, ACL reconstruction rates in Australian children under 14 have climbed 6% annually [5,6]. Age and sex influence injury distribution. Incidence peaks in adolescence and early adulthood: males aged 19–24 have the highest rate (241 per 100,000), while females peak earlier (14–18 years) at 228 per 100,000 [7-9]. Sex disparities are stark—females face 2–7 times higher risk in similar sports, driven by anatomical, hormonal, and neuromuscular factors.

3.2. Sport-specific and occupational risks

Sport-specific demands are key drivers of ACL injury. Basketball and soccer are the top contributors, due to frequent cutting, deceleration, and aerial movements. Contact mechanisms (e.g., lateral blows) cause significant injuries in American football and rugby, while gymnastics and skiing pose risks via wide-ranging motions and twisting landings [7]. Notably, non-contact mechanisms dominate across most sports, highlighting the role of neuromuscular and biomechanical factors [8]. Beyond sports, occupational and lifestyle factors contribute. Sedentary lifestyles weaken neuromuscular control, making individuals vulnerable to injury during sudden activity [10]. Elevated BMI also raises risk by increasing knee joint stress during sports.

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3.3. Recurrence, long-term consequences and special populations

Recurrence and bilateral injuries are significant concerns—up to 25% of young athletes experience a second ACL injury (ipsilateral graft rupture or contralateral tear) within two years of returning to sports. This is linked to persistent neuromuscular deficits, early return to play, and psychological factors like fear of re-injury. Long-term consequences are common: over 50% of ACL injury patients develop radiographic osteoarthritis within 10–15 years, regardless of surgical intervention [8]. Special populations require targeted attention. Female athletes face a higher risk due to anatomical, hormonal, and neuromuscular traits, though prevention programs can mitigate this. Older adults experience fewer ACL injuries (often during recreational activities like skiing) but face greater comorbidities, requiring specialized management. Adolescents are at elevated risk due to early specialization, high training volumes, and growth-related factors (open physes, developing neuromuscular control), complicating both risk mitigation and treatment [10].

4. Diagnostic impact and evaluation methods

4.1. Clinical assessment: history and physical examination

Accurate, timely diagnosis of ACL injury is critical to ensure proper treatment, reduce secondary joint damage, and improve long-term outcomes [1]. Diagnostic approaches have evolved from basic physical exams to advanced imaging and AI-assisted technologies, with a multimodal strategy often needed for optimal evaluation [2,3]. A comprehensive patient history is the first diagnostic step. Patients with acute ACL rupture often report a traumatic event (abrupt stopping, turning, landing) followed by a “pop” in the knee [4]. History also clarifies injury mechanism (contact vs. non-contact), which informs assessment of concurrent damage [6].

Physical examination relies on standardized tests. The Lachman test is most sensitive (85–90%) for ACL rupture, especially in the acute phase—it involves flexing the knee 20–30 degrees to assess tibial displacement; increased displacement with a soft endpoint indicates ACL dysfunction [8,9]. The anterior drawer test (performed at 90 degrees of flexion) is less sensitive due to hamstring tension [10]. The pivot-shift test evaluates rotational instability and has high specificity, while the leverage sign test (a newer method) assesses functional instability, though further validation is needed. Acute pain, swelling, or muscle spasms can reduce exam accuracy, often requiring follow-up after inflammation subsides [9].

4.2. Imaging modalities and emerging technologies

Imaging is vital for confirming ACL injury and evaluating associated damage. X-rays cannot directly visualize the ACL but rule out fractures (e.g., Segond fractures, tibial intercondylar avulsions) and assess joint alignment or degenerative changes. MRI is the gold standard, with >90% sensitivity and specificity—it confirms partial or complete ACL tears, identifies meniscal/cartilage damage, and detects characteristic bone contusions (lateral femoral condyle, tibial plateau). MRI findings guide surgical planning and prognosis. Ultrasound offers real-time dynamic imaging but is less accurate than MRI and operator-dependent; it is used primarily for resource-limited settings or dynamic assessments [7-9]. Emerging technologies are transforming diagnosis. AI and machine learning models (e.g., convolutional neural networks like ELNet) accelerate MRI analysis and improve accuracy, outperforming radiologists in interpretation time for ACL tears. Self-supervised learning on dynamic MRI sequences detects functional instability missed by static imaging.

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Wearable sensors and motion analysis tools identify aberrant biomechanics, enabling pre-injury risk assessment.

5. Prevention and rehabilitation strategies

5.1. Principles and evidence-based prevention programs

ACL injuries are highly disabling due to their high incidence, prolonged recovery, and long-term sequelae (e.g., post-traumatic osteoarthritis) [1]. Effective prevention and rehabilitation strategies aim to reduce initial injury risk, optimize functional recovery, and lower re-injury odds [2,3]. Key principles include neuromuscular training (improving hamstring-quadriceps balance), plyometric/agility exercises (teaching soft landings and avoiding valgus collapse), proprioceptive/balance training (enhancing joint awareness), technique modification (proper cutting/pivoting), and sport-specific conditioning [5]. These programs are most effective for high-risk groups like female adolescent athletes [4].

Evidence-based programs have proven efficacy. The FIFA 11+ (a structured warm-up with running, core stability, balance, and strength exercises) reduces ACL injury risk by 30–50% in soccer players [8]. The PEP (Prevent Injury and Enhance Performance) Program, designed for female athletes, lowers ACL injuries in basketball and soccer via landing mechanics and agility training [9]. Nordic Hamstring and Copenhagen Adductor Exercises indirectly reduce ACL risk by improving muscle balance [10]. Compliance (performing programs 2–3 times weekly during competition season) is critical, though awareness and time constraints hinder implementation.

5.2. Phase-oriented rehabilitation and psychological considerations

Rehabilitation uses a criterion-based, phase-oriented approach (not strict timelines) for both surgical and non-surgical cases. Phase 1 (0–2 weeks: Acute Recovery) focuses on reducing pain/swelling, restoring knee extension, and activating quadriceps via cryotherapy, patellar mobilization, and straight-leg raises. Phase 2 (2–6 weeks: Intermediate Strengthening) improves strength (mini-squats, leg presses), range of motion, and gait, adding proprioceptive training (balance boards). Phase 3 (6–16 weeks: Advanced Training) enhances dynamic stability via plyometrics (jumping, bounding) and agility drills [7]. Phase 4 (4–6 months: Sport-Specific Training) prepares athletes for high-intensity movements (cutting, sprinting) using objective criteria (limb symmetry index >90%) [8]. Phase 5 (6–12 months: Return to Sport) requires strength symmetry >95%, no pain/swelling, and medical approval [9]. Psychological preparedness is often overlooked but critical—up to 50% of athletes do not return to pre-injury sport due to fear of re-injury, anxiety, or lost confidence [10]. Interventions like goal-setting, visualization, and gradual exposure to sport-specific drills boost motivation. Tools like the ACL-Return to Sport after Injury (ACL-RSI) scale assess psychological readiness.

5.3. Re-injury challenges, public health and future directions

Re-injury remains a major challenge—25% of athletes experience a second ACL injury within two years of return to sport. Risk factors include premature return, persistent neuromuscular deficits, and inadequate rehabilitation. Strategies to mitigate this include extended rehabilitation (each month beyond 9 months reduces re-injury risk by 51%), wearable technology (monitoring biomechanics), biological augmentation (PRP, stem cells for graft healing), and customized protocols. From a public health perspective, investing in prevention reduces healthcare costs—mandatory programs in youth sports could lower incidence and long-term disability [9]. Future directions include integrating AI,

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wearable tech, and psychological support into prevention/rehabilitation, along with expanding access to advanced diagnostic and therapeutic resources [8].

6. Conclusion

ACL injuries represent a multifaceted challenge spanning acute trauma management to long-term joint health preservation, with profound impacts on athletic performance, quality of life, and public health systems globally. Key findings from this study highlight the critical role of understanding multifactorial injury mechanisms—where non-contact injuries dominate (70–80%) and arise from interactions between intrinsic (anatomical, hormonal, genetic) and extrinsic (sport, fatigue, surface) factors—especially for high-risk groups like female athletes and adolescents. Diagnostically, the evolution from traditional physical exams to MRI and AI-driven technologies has significantly improved accuracy, but structured workflows and multidisciplinary collaboration remain essential to avoid delayed diagnosis and secondary damage (e.g., meniscal tears, early osteoarthritis). In treatment and rehabilitation, personalized approaches—surgical reconstruction for young, active patients versus conservative care for older or less active individuals—paired with phase-oriented, criterion-based rehabilitation (emphasizing neuromuscular control and sport-specific training) are foundational. Psychological support, often overlooked, is critical to addressing fear of re-injury and low confidence, which prevent up to 50% of athletes from returning to pre-injury sport levels. Prevention, though the most cost-effective strategy, remains underutilized; evidence-based programs like FIFA 11+ and PEP can reduce injury risk by 30–50%, but their impact is limited by poor compliance, lack of awareness, and inadequate institutional support. Challenges persist, including unacceptably high re-injury rates (25% within two years) and long-term osteoarthritis risk (over 50% within 10–15 years post-injury). Future progress must focus on extending rehabilitation timelines, integrating wearable biomechanical monitoring, exploring biological augmentations (e.g., PRP, stem cells), and scaling prevention programs through policy mandates in youth sports. Ultimately, addressing ACL injuries requires a continuum of care—from pre-injury prevention to long-term management—driven by interdisciplinary collaboration between clinicians, researchers, coaches, and policymakers. By prioritizing both physical and psychological recovery and embedding prevention into sports culture, we can reduce the global burden of ACL injuries and improve long-term joint health for all affected populations.

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