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Letter to Editor

An Editorial Perspective on Modifiable Risk Factors Before and After Anterior Cruciate Ligament Reconstruction: Strategies for Optimizing Long-Term Outcomes and Mitigating Osteoarthritis

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Abstract
Anterior cruciate ligament reconstruction (ACLR) is a common orthopedic procedure, yet individuals post-ACLR face a significantly elevated risk of developing post-traumatic osteoarthritis (PTOA), exceeding 50% within 10–15 years. This narrative synthesis interprets current evidence and clinical viewpoints to highlight modifiable risk factors influencing long-term outcomes and proposes actionable strategies for joint preservation. This perspective utilizes a narrative synthesis approach to interpret the existing literature. The search strategy involved utilizing keywords, such as "anterior cruciate ligament reconstruction," "post-traumatic osteoarthritis," "rehabilitation," and "modifiable risk factors" across databases, including PubMed and Scopus, to inform the presented synthesis spanning recent years. Key modifiable risk factors are categorized into pre-operative and post-operative phases. Pre-operatively, factors, such as quadriceps weakness, loss of full extension, aberrant movement patterns, joint effusion, and low psychological readiness, are critical targets. Post-operatively, persistent strength deficits, poor movement quality, inadequate load management, and elevated body mass index are associated with increased PTOA risk. Evidence-based strategies, such as pre-habilitation, criterion-based rehabilitation, neuromuscular training, and lifelong maintenance programs, demonstrate a relationship with risk mitigation. The high prevalence of PTOA following ACLR is not inevitable. By systematically addressing modifiable risk factors through targeted, objective, and sustained interventions, clinicians can significantly improve long-term joint health and functional outcomes.

Keywords: Anterior cruciate ligament, Osteoarthritis, Reconstruction, Rehabilitation

Introduction
Anterior cruciate ligament reconstruction (ACLR) is a devastating injury, predominantly affecting active individuals. While ACLR is often successful in facilitating a return to sport (RTS), it fails to fully restore the knee to its pre-injury biological state (1). The subsequent development of post-traumatic osteoarthritis (PTOA) represents a major public health concern, leading to pain, functional limitations, and reduced quality of life many years after the initial surgery (2). The etiology of PTOA after ACLR is multifactorial, involving a complex interplay of biological, mechanical, and patient-specific factors. While non-modifiable factors (e.g., age, genetics, concomitant meniscal/chondral injury) contribute to risk, a growing body of evidence points to several modifiable factors that clinicians and patients can

target (3). This editorial delineates these factors across the treatment timeline, proposing actionable strategies to optimize outcomes and protect the joint (4).

The period between injury and surgery is not a passive waiting window but a critical opportunity to influence surgical outcomes and long-term joint health (5). Several modifiable risk factors must be addressed during this pre-operative phase. First, neuromuscular control and movement patterns often deteriorate, as the ACL-deficient knee develops compensatory strategies, such as a quadriceps avoidance gait or dynamic valgus. Allowing these patterns to persist reinforces abnormal joint loading, making it essential to implement structured pre-habilitation focused on restoring gait symmetry, reducing effusion, and re-educating proper movement patterns, such as landing and deceleration in a controlled environment (6). Another critical factor is quadriceps strength and activation, where arthrogenic muscle inhibition leads to rapid and profound atrophy and weakness, a strong predictor of poor post-operative function (7). This requires effective management of pain and effusion through cryotherapy, compression, and elevation, combined with neuromuscular electrical stimulation and voluntary isometric exercises to combat inhibition and preserve muscle mass (8). Furthermore, achieving full range of motion prior to surgery is vital, as pre-operative loss of full extension is strongly correlated with post-operative stiffness and arthrofibrosis (9). The strategy here involves working to attain full, active knee extension and at least 120 degrees of flexion through targeted stretching and low-load, prolonged-duration extension exercises (9). Finally, psychological readiness cannot be overlooked, as fear of re-injury, anxiety, and low self-efficacy are significant barriers to recovery and a successful RTS (10). Integrating psychological screening using tools, such as the ACL-RTS after Injury scale or the Tampa Scale of Kinesiophobia, along with early counseling and goal-setting, helps build resilience and realistic expectations for the journey ahead (10). This narrative synthesis interprets current evidence and clinical viewpoints to highlight modifiable risk factors influencing long-term outcomes and proposes actionable strategies for joint preservation.

Materials and Methods

This study is based on a narrative synthesis approach designed to integrate and interpret current evidence regarding modifiable risk factors influencing long-term outcomes after ACLR. A structured literature search was conducted across major databases, including PubMed, Scopus, and Web of Science, up to April 2026, using keywords, such as "anterior cruciate ligament reconstruction," "post-traumatic osteoarthritis," "rehabilitation," "modifiable risk factors," "neuromuscular control," and "pre-habilitation." Peer-reviewed articles, systematic reviews, clinical guidelines, and consensus statements focusing on rehabilitation strategies or osteoarthritis mitigation following ACLR were considered for inclusion, while non-human studies, case reports, and articles unrelated to modifiable or intervention-based factors were excluded. The process prioritized high-quality clinical and biomechanical studies that addressed both pre-operative and post-operative phases. The gathered evidence was then organized and synthesized using a narrative approach, emphasizing clinical applicability and mechanism-based reasoning rather than quantitative data pooling. Sources demonstrating converging outcomes or strong consensus among clinical experts were synthesized as evidence-based recommendations, while less consistent data were discussed from theoretical or expert-opinion perspectives. This method allowed for an integrative interpretation of findings across biological, mechanical, and psychosocial domains, ultimately aiming to generate a cohesive clinical perspective for optimizing long-term joint health following ACLR.

Results

Table 1 presents a summary of the key pre-operative modifiable risk factors and corresponding intervention strategies.

The post-operative and long-term phase of rehabilitation must extend far beyond the typical 6–9 month return-to-sport timeline to effectively address chronic risk factors for PTOA (4). Table 2 summarizes the key rehabilitation phases, associated modifiable targets, and their rationale for osteoarthritis mitigation. A primary concern is failing to implement comprehensive, criterion-based rehabilitation, as adherence to arbitrary time-based milestones instead of objective functional criteria is a major pitfall (8, 10). The strategy is to implement a phased, criterion-based protocol where progression is contingent on achieving specific benchmarks, such as strength and hop performance, demonstrating a limb symmetry index (LSI) of at least 90%, and validated movement quality, rather than simply elapsed time (6). Furthermore, persistent quadriceps and hip strength deficits are highly problematic, as quadriceps weakness remains one of the most consistent findings post-surgery and is strongly linked to functional limitations and cartilage degradation (7). The strategy must emphasize high-intensity, progressive resistance training throughout the entire rehabilitation continuum and beyond, with a focus on both the quadriceps and the posterior chain, including the hamstrings and gluteal muscles, to control dynamic knee stability (3). Even after returning to sport, movement quality and biomechanics often remain impaired, with individuals demonstrating stiffened movement strategies and altered kinematics during sport-specific tasks, leading to asymmetric joint loading (11). To counter this, integrating advanced neuromuscular training, including plyometric, agility drills, and sport-specific simulations with a continuous focus on quality, such as proper knee-over-toe alignment and soft landings, is essential, potentially using video or motion analysis for feedback (3). Secondary prevention and load management are also critical, given that the highest risk of a second ACL injury occurs within the first two years after returning to sport, and poor load management can contribute to overuse symptoms and joint stress (6, 12). The strategy involves developing structured, gradual return-to-sport plans that carefully monitor training volume and intensity, while educating the individual on the importance of incorporating continued strength and conditioning as a permanent part of their athletic routine (4, 12). Finally, body weight and metabolic health play a significant role, as an elevated body mass index increases compressive forces across the knee joint and is associated with systemic low-grade inflammation that may accelerate osteoarthritis. Therefore, incorporating nutritional counseling and lifestyle modifications to achieve and maintain a healthy body weight should be framed as a direct and vital intervention for long-term joint health (12).

Table 1. Key Pre-operative Modifiable Risk Factors and Intervention Strategies

Modifiable risk factor	Clinical Impact if Unaddressed	Evidence-Based Pre-Habilitation Strategies	Evidential Basis (Consensus/Expert Opinion)
Quadriceps AMI and weakness	Poor surgical outcomes, delayed rehab, persistent strength deficits.	NMES, isometric quad sets, straight leg raises with biofeedback.	Consensus
Loss of full extension	High risk of post-op arthrofibrosis, altered gait mechanics.	Prone hangs, heel props, low-load prolonged stretching.	Consensus
Aberrant movement patterns	Reinforcement of pathological loading, increased contralateral limb risk.	Gait retraining, hip-dominant squat/landing technique, perturbation training.	Expert opinion
Joint effusion and pain	Exacerbates AMI, limits participation in rehab.	PRICE principles, modalities, isometric exercise for pain modulation.	Consensus
Low psychological readiness	Poor adherence, delayed RTS, higher re-injury rates.	Education, goal-setting, cognitive-behavioral strategies, peer mentoring.	Consensus

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Table 2. Post-operative Rehabilitation Phases with Modifiable Targets for Osteoarthritis (OA) Mitigation

Phase	Primary Goals	Key Modifiable Targets and Metrics	OA Mitigation Rationale	Data Source/Interpretation
Early (0–6 weeks)	Protect graft, restore ROM, reduce effusion, activate quads.	Full extension, quad activation (via NMES/sets), minimal effusion.	Prevents arthrofibrosis; combats early AMI to preserve muscle.	Direct from study
Intermediate (6 weeks–3 month)	Restore gait, improve strength/balance, normalize movement.	Single-leg balance, hip and quad strength (isokinetic/dynamometry), step-down quality.	Builds foundational strength for load distribution; improves sensorimotor control.	Synthesized interpretation
Late (3–6 months)	Build power/endurance, prepare for sport-specific demands.	Strength LSI ≥80%, hop test LSI ≥80%, flawless movement on agility drills.	Ensures adequate strength and control before high-impact activities.	Direct from study
Return-to-sport (6+ months)	Safe return to activity, prevent re-injury.	Clearance criteria: Strength LSI ≥90%, hop battery LSI ≥90%, psychological readiness, sport-specific fitness.	Directly addresses key re-injury and long-term loading risk factors.	Consensus
Long-term maintenance (lifelong)	Sustain joint health, optimize performance.	Continued strength training (≥2x/wk), maintenance of ideal body weight, mindful load management.	Counters chronic strength deficits and abnormal loading linked to PTOA.	Synthesized interpretation

Biological Mechanisms and Implementation Challenges

Deep Dive into Biological Mechanisms of Post-Traumatic Osteoarthritis (PTOA)

While the mechanical implications of ACL deficiency are well-established, the ensuing biological cascade significantly accelerates PTOA risk. Following ACL rupture, the immediate mechanical instability causes a shift in the cellular environment within the joint capsule. Synovial fluid analysis often reveals elevated levels of pro-inflammatory cytokines, particularly interleukin-1 beta and tumor necrosis factor-alpha, which are potent drivers of catabolic activity in chondrocytes. These cytokines promote the expression of matrix metalloproteinases and a disintegrin and metalloproteinase with thrombospondin motifs, enzymes responsible for the breakdown of Type II collagen and aggrecan, the essential components of articular cartilage matrix. Furthermore, alterations in joint homeostasis lead to metabolic shifts; chondrocytes in the ACL-deficient knee may exhibit a shift toward anaerobic glycolysis due to transient ischemia or altered mechanical signaling, compromising their ability to maintain the extracellular matrix and repair minor damage, thereby accelerating the degenerative process over time. Addressing modifiable factors, especially maintaining muscle strength and controlled loading, functions to dampen this inflammatory and catabolic response by normalizing intra-articular pressures and reducing chronic mechanical irritation.

Implementation Challenges and Paradigm Shift

Despite a robust and growing evidence base outlining the critical modifiable risk factors for PTOA after ACLR, a significant translational gap persists between this knowledge and consistent widespread clinical practice (4). The implementation of the comprehensive, long-term strategies outlined in this editorial faces substantial multi-level barriers.

Practical Barriers and Conflicts

At a practical level, barriers to implementation are manifold. Many clinical settings lack access to the objective measurement tools, such as isokinetic dynamometers or 3D motion capture necessary for the rigorous, criterionbased progression advocated here (3). Time constraints within standard rehabilitation protocols and payer-driven limitations on the number of authorized physical therapy visits directly conflict with the need for extended, high-quality care focused on long-term outcomes (4). Furthermore, a powerful cultural narrative, often driven by athletes, coaches, and families, prioritizes an expedited RTS over the methodical, criteria-driven process essential for joint health. This external pressure can lead to premature clearance based on time elapsed rather than functional readiness, inadvertently elevating re-injury and long-term degenerative risks (6).

The Need for a New Conceptual Model

These challenges underscore the necessity for a fundamental paradigm shift in how ACL injury and reconstruction are conceptualized. The prevailing model often views ACLR as a definitive solution to an acute problem. We must instead reframe it as the treatment of an initial inciting event within a potential lifelong degenerative pathway (PTOA) (2). Consequently, the metrics of success must be expanded. While a timely RTS and the absence of graft failure are important short-term outcomes, they are insufficient benchmarks. True success must be equally measured by the preservation of joint health, the maintenance of high-level function, and the mitigation of osteoarthritic symptoms a decade or more after surgery (2,6,10).

Actionable Strategies for Translational Change

To operationalize this shift, we propose several actionable strategies for clinicians, researchers, and healthcare systems (3,7,8): Standardized Adoption of Objective Criteria: Move decisively away from time-based rehabilitation. Clinical practice must integrate standardized, accessible test batteries including validated strength assessments (e.g., isokinetic or handheld dynamometry), hop tests, and movement quality screens as mandatory checkpoints for any RTS decision. Advocacy for Extended Rehabilitation Models: The clinical community must advocate for healthcare policy and insurance models that recognize and fund rehabilitation as a long-term investment in health. This includes supporting "pre-habilitation" programs and extended care models that focus on the transition back to activity and lifelong maintenance, mirroring the chronic disease management approach.

Comprehensive Patient Education and Psychological Integration: Patients should be empowered from the outset with the knowledge that their ACL injury initiates a lifelong relationship with knee health. Education must explicitly link adherence to modifiable behaviors strength training, load management, and weight control to the long-term risk of PTOA. Furthermore, routine screening for and addressing psychological factors, such as kinesiophobia and low self-efficacy, must be a standard component of rehabilitation. Fostering interdisciplinary, longitudinal collaboration: effective care requires breaking down silos. A seamless continuum must be established, involving the surgeon, physical therapist, athletic trainer, and strength and conditioning coach. This team should guide the athlete not only from surgery to RTS but through the high-risk subsequent years and into a sustainable, joint-healthy athletic lifestyle.

In conclusion, bridging the gap from evidence to practice requires confronting these practical barriers while championing a new conceptual model. By embracing a biopsychosocial framework that extends the rehabilitation timeline and prioritizes objective, function-driven milestones, clinicians can transform the post-ACLR trajectory. The goal is unequivocal: to evolve from restoring short-term stability to being stewards of long-term joint health, thereby altering the disappointing natural history of this consequential injury.

Conclusion

The high prevalence of PTOA following ACLR is not an inevitable outcome but a condition whose risk is modifiable. By aggressively targeting pre-operative neuromuscular deficits, adhering to rigorous criterion-based rehabilitation, addressing persistent strength and biomechanical flaws, and promoting lifelong joint-healthy behaviors, clinicians can significantly alter the trajectory of the post-ACLR knee. The goal must evolve from a short-term focus on RTS to a long-term commitment to preserving the articular cartilage and ensuring decades of functional, pain-free activity for our patients.

Ethics Approval and Consent to Participate

Not applicable.

Consent for Publication

Not applicable.

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Authors' Contributions

Ebrahim Piri and AmirAli Jafarnezhadgero contributed equally to the conception, drafting, and revision of the manuscript. All authors read and approved the final version.

Conflict of Interest

The authors declared no conflicts of interest.

Declaration of Generative (AI) in Scientific Writing

No AI tools or technologies were used in the preparation of this manuscript.

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