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Reconstruction of the Anterior Cruciate Ligament in Athletes – A Review of Methods and Treatment Outcomes

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ABSTRACT

Background: ACL injuries are common in sports requiring rapid deceleration, pivoting, and sudden directional changes. Given their high incidence, optimizing reconstruction techniques and rehabilitation is crucial for knee stability, reinjury prevention, and return-to-sport success.

Objective: This systematic review evaluates ACL reconstruction techniques, rehabilitation protocols, and return-to-sport outcomes, focusing on graft selection, surgical advancements, rehabilitation strategies, and reinjury risk factors.

Methods: A comprehensive literature search was conducted using PubMed, Scopus, Web of Science, and Google Scholar, covering studies from 2000 to 2025. Studies included focused on ACL reconstruction techniques, rehabilitation interventions, and return-to-sport outcomes in athletes. Key factors analyzed included graft type, surgical methods, rehabilitation phases, return-to-sport timelines, and long-term complications.

Results: Autografts, particularly bone-patellar tendon-bone (BPTB) and quadriceps tendon grafts, provide superior biomechanical strength and lower failure rates compared to allografts and synthetic grafts. Allografts, though viable for lower-demand patients, have higher failure rates in young athletes. Rehabilitation plays a critical role in optimizing recovery, with neuromuscular training and psychological readiness influencing return-to-sport outcomes. Despite surgical advancements, return-to-sport rates remain suboptimal, with only 55-65% of athletes regaining pre-injury performance within two years. Psychological barriers, such as fear of reinjury, contribute to delays and increased risk of secondary injuries.

Conclusions: While surgical and rehabilitation improvements have enhanced ACL reconstruction outcomes, challenges persist in optimizing return-to-sport rates and reducing reinjury risks. Future research should explore rehabilitation optimization, psychological interventions, regenerative therapies, and AI-driven rehabilitation tools to improve long-term athletic outcomes.

Keywords: ACL reconstruction, anterior cruciate ligament injury, autograft, allograft, synthetic grafts, rehabilitation, return to sport, reinjury risk, knee stability, sports medicine

1. Introduction

ACL injuries represent a major concern in sports medicine, with an incidence of approximately 200,000 cases per year in the United States alone. These injuries occur most frequently in sports that involve rapid deceleration, pivoting, and abrupt changes in direction, such as soccer, basketball, football, and skiing. The mechanism of injury typically involves a combination of valgus knee collapse and rotational stress, often during non-contact movements. Studies indicate that up to 70% of ACL injuries are non-contact in nature, resulting from biomechanical and neuromuscular imbalances that predispose athletes to excessive knee loading. Non-contact ACL injuries commonly occur when an athlete attempts a sudden change in direction, lands from a jump with an extended knee, or decelerates rapidly while cutting or pivoting. These movements place excessive stress on the ACL, particularly if the quadriceps overpower the hamstrings, leading to anterior tibial translation. Deficits in neuromuscular control, including poor landing mechanics and weak hip and core stability, further increase the risk. Additionally,

improper foot positioning, such as excessive pronation, can contribute to increased knee valgus and ACL strain. Direct trauma, such as collisions in football or rugby, can also contribute to ACL injuries, though these are less common compared to non-contact mechanisms. Additionally, female athletes are at a higher risk of ACL tears due to anatomical and hormonal differences, including a wider pelvis, increased ligament laxity, and altered neuromuscular control.

The primary goal of ACL reconstruction is to restore knee stability, prevent long-term complications such as osteoarthritis, and facilitate a safe return to sports. Given the high physical demands placed on athletes, selecting the optimal reconstruction method is crucial for ensuring functional recovery and reducing reinjury risk. Understanding the mechanisms of ACL injury is essential for developing preventive strategies, improving surgical outcomes, and designing rehabilitation protocols that minimize recurrence rates.

2. Methodology

2.1 Study Design

This review follows a systematic approach to synthesizing existing research on ACL reconstruction methods, rehabilitation strategies, and return-to-sport outcomes. A qualitative synthesis of peer-reviewed studies, clinical trials, and meta-analyses published in the last two decades was conducted. The focus is on surgical and non-surgical techniques, post-operative rehabilitation, and factors influencing reinjury rates among athletes.

2.2 Search Strategy

A comprehensive literature search was performed using electronic databases, including PubMed, Scopus, Web of Science, and Google Scholar. The search covered studies published between 2000 and 2025, prioritizing human-based research. The following search terms and Boolean operators were used to refine results: ("ACL reconstruction" OR "anterior cruciate ligament surgery" OR "ACL repair" OR "ACL graft choice") AND ("return to sport" OR "functional recovery" OR "knee stability") AND ("rehabilitation" OR "neuromuscular training" OR "psychological readiness") AND ("reinjury risk" OR "failure rate" OR "graft longevity") AND ("biological augmentation" OR "stem cells" OR "PRP") AND ("athletes" OR "high-performance sports" OR "elite sports").

Additional references were identified through backward citation tracking of key systematic reviews and meta-analyses.

2.3 Inclusion and Exclusion Criteria

Inclusion Criteria:

- Peer-reviewed studies investigating ACL reconstruction techniques and outcomes in athletes.
- Research involving human participants, particularly elite and amateur athletes.
- Studies assessing functional recovery, graft failure rates, return-to-sport timelines, and rehabilitation protocols.
- Clinical trials and cohort studies evaluating different surgical approaches and rehabilitation interventions.
- Studies utilizing objective assessment tools, such as isokinetic strength testing, limb symmetry index, and functional hop tests.
- Publications in English between 2000 and 2025.

Exclusion Criteria:

- Studies focusing solely on animal models without human validation.
- Research on ACL injuries in non-athletic populations.
- Studies lacking clear methodology or outcome measures.
- Non-peer-reviewed literature, case reports, or conference abstracts without methodological details.
- Articles without a direct focus on ACL reconstruction, rehabilitation, or return-to-sport outcomes.

2.4 Data Extraction and Analysis

Key data were extracted from eligible studies, including:

- Study characteristics: Author(s), year, sample size, participant characteristics (age, sex, sport type, competition level).
- Methodology: Study design (e.g., randomized controlled trial, retrospective cohort study), surgical techniques (single-bundle vs. double-bundle, autograft vs. allograft), rehabilitation protocols, and psychological assessments.
- Key findings: Graft success rates, rehabilitation timelines, functional recovery, reinjury rates, and psychological impact on return to play.

A qualitative synthesis was performed to identify trends, inconsistencies, and gaps in the literature. Studies were categorized based on surgical method, rehabilitation strategy, and return-to-sport success. Methodological differences across studies were critically analyzed to assess reliability and validity.

2.5 Ethical Considerations

As this study is a literature review, it does not involve direct human or animal research and does not require ethical approval. However, all referenced studies were screened to ensure adherence to ethical research practices, as indicated by institutional review board (IRB) approvals in the original studies.

2.6 Limitations of Methodology

Several limitations should be considered in this review. The variability in rehabilitation protocols, surgical techniques, and return-to-sport criteria across studies introduces challenges in drawing uniform conclusions. Individual differences in patient demographics, training intensity, and psychological readiness further contribute to variability in outcomes. Additionally, the lack of long-term follow-up data in many studies limits the ability to assess sustained recovery and reinjury risk. Future research should focus on standardized rehabilitation protocols, larger sample sizes, and longitudinal studies to enhance.

3. Surgical Techniques for ACL Reconstruction

3.1 Autografts

Autografts, obtained from the patient's own tissue, remain the gold standard for ACL reconstruction due to their superior biomechanical properties and lower failure rates compared to allografts(Paschos & Vasiliadis, 2013). The most commonly used autografts include bone-patellar tendon-bone (BPTB), hamstring tendon, and quadriceps tendon grafts.

The BPTB graft offers strong initial fixation and faster bone integration, making it a preferred choice among high-performance athletes(Frank et al., 2017). However, its use is associated with anterior knee pain, patellar tendinopathy, and an increased risk of patellar fractures, particularly in patients with smaller patellar anatomy(Lazarides et al., 2018). Some studies suggest that the risk of patellofemoral pain syndrome is higher in patients undergoing BPTB grafting compared to other techniques, potentially impacting long-term functional outcomes(Hannon et al., 2020).

The hamstring tendon graft provides good biomechanical properties, with lower donor site morbidity and reduced anterior knee pain compared to BPTB grafts (Baawa-Ameyaw et al., 2021). However, there is evidence that hamstring grafts may lead to reduced hamstring strength postoperatively, which can influence knee stability and increase reinjury risk (Ebert et al., 2024). Recent biomechanical analyses suggest that hamstring grafts, despite their lower morbidity, may present an increased risk of laxity when compared to BPTB grafts, particularly in cutting and pivoting sports (S. Li et al., 2012).

The quadriceps tendon graft is increasingly used due to its adequate strength, larger graft diameter, and lower complication rates compared to BPTB. Studies suggest that quadriceps tendon autografts provide similar functional outcomes to BPTB while reducing donor site morbidity and postoperative pain (Krumbach et al., 2024). Additionally, the quadriceps graft has shown promising results in younger, high-demand athletes, with comparable return-to-sport rates and reinjury risk to traditional autografts (Rizvanovic et al., 2023). Recent studies indicate that quadriceps tendon grafts may be biomechanically superior in terms of graft stiffness and load-to-failure ratios, contributing to their growing popularity(Shani et al., 2016).

Recent systematic reviews suggest that the choice of autograft should be individualized based on patient activity level, anatomical factors, and risk of donor site morbidity (Sollberger et al., 2023). Further research is needed to determine the optimal graft choice in elite athletes participating in pivoting sports. Future studies should focus on long-term comparative outcomes and biomechanical durability among the different autograft options to optimize surgical decision-making.

3.2 Allografts

Allografts, derived from cadaveric tissue, reduce donor site morbidity and shorten surgical time, making them an attractive option for ACL reconstruction, particularly in patients who wish to avoid the risks associated with harvesting autografts. However, allografts are associated with slower biological incorporation, as they lack viable cells and require revascularization and remodeling to integrate into the host tissue. This delayed incorporation increases the risk of graft failure, especially in younger and more active athletes. Studies indicate that allograft failure rates can be high, particularly in patients under 25 years old, compared to autografts (Iosifidis & Tsarouhas, 2012). The failure risk is influenced by factors such as the sterilization method used for the allograft, with irradiation and chemical processing potentially weakening the structural integrity of the graft (Vopat et al., n.d.). Moreover, some studies suggest that the immune response to allografts, despite reduced antigenicity, may play a role in delayed healing and inferior biomechanical properties compared to autografts (Prokopis & Schepsis, n.d.). While allografts remain a viable option for older, less active patients, their use in high-performance athletes should be approached with caution, and newer strategies such as biological augmentation and tissue engineering are being explored to improve integration and long-term durability (Runer et al., 2023).

3.3 Synthetic Grafts

Synthetic materials such as LARS (Ligament Advanced Reinforcement System) and polyethylene terephthalate (PET)-based grafts have been explored as alternatives for ACL reconstruction, particularly in cases where biological grafts are unavailable or contraindicated. These synthetic grafts aim to provide an immediate structural replacement while allowing native tissue ingrowth and remodeling. However, concerns regarding long-term durability, mechanical wear, and biocompatibility remain significant barriers to widespread adoption. Studies have shown that synthetic grafts are associated with higher rates of graft failure, inflammatory reactions, and synovitis compared to autografts and allografts (Ventura et al., 2010) . Additionally, long-term follow-up data suggest an increased risk of graft elongation, leading to knee instability and higher revision surgery rates (Legnani et al., 2010). Despite these challenges, newer generations of synthetic grafts incorporating bioresorbable materials and tissue engineering approaches are being investigated to improve integration and longevity (*Bourke2004*, n.d.). Further research is needed to determine their clinical efficacy, particularly in high-performance athletes who require superior biomechanical properties and long-term stability.

3.4 Modern Surgical Techniques

Recent advancements in ACL reconstruction have introduced new techniques that aim to improve graft longevity, biomechanical properties, and post-operative recovery.

One of the key debates in ACL reconstruction is the choice between single-bundle and double-bundle reconstruction techniques. The single-bundle technique, which has been the traditional approach, reconstructs the anteromedial bundle of the ACL, providing adequate rotational stability for most patients. However, research suggests that the double-bundle technique, which reconstructs both the anteromedial and posterolateral bundles, may more closely replicate native ACL biomechanics and offer better rotational stability (Y. L. Li et al., 2014). Some studies indicate that double-bundle reconstruction may lead to improved functional outcomes and lower graft failure rates, particularly in high-demand athletes, though long-term comparisons remain inconclusive (Gharpinde et al., 2024).

Technological advancements in navigation and robotic-assisted surgery have also gained traction in ACL reconstruction. Computer-assisted techniques allow for greater precision in tunnel placement, which is a critical factor in graft longevity and knee stability. Robotic-assisted procedures have demonstrated improved alignment accuracy and reduced intraoperative variability, potentially decreasing failure rates and enhancing patient outcomes

(Bourgeault-Gagnon et al., 2024). However, widespread adoption is limited by high costs and the need for specialized training.

4. Treatment Outcomes – Analysis of ACL Reconstruction Effectiveness in Athletes

4.1 Criteria for Successful ACL Reconstruction

The success of ACL reconstruction is determined by several key factors, including the restoration of full knee function, absence of pain or instability, and the ability to return to sport at a pre-injury level. Full knee function is assessed through objective measures such as range of motion, muscle strength, and ligament stability tests. Athletes who achieve symmetrical quadriceps and hamstring strength, along with adequate proprioception, have better post-surgical outcomes (Cunha & Solomon, 2022). Pain and instability must also be minimized to ensure confidence in knee function, with studies indicating that persistent pain and subjective instability are associated with a higher risk of re-injury (ADHITYA et al., 2023) . Return to sport at the pre-injury level remains the ultimate goal, yet research suggests that only 55-65% of athletes successfully return to competitive play within two years post-surgery (Ardern et al., 2014). Factors such as psychological readiness, adherence to rehabilitation, and sport-specific demands play significant roles in determining return-to-sport success (Miguel et al., 2024).

4.2 Return to Sport – Key Indicators

The timeline for returning to sport varies depending on several factors, including surgical technique, rehabilitation protocol, and the physical demands of the sport. Key factors influencing a rapid return to sport include early restoration of range of motion, progressive strength training, and neuromuscular control (Buckthorpe, 2019). Studies indicate that athletes in lower-impact sports, such as swimming or cycling, may resume competition within 6-8 months, while high-impact sports such as soccer, basketball, and American football typically require 9-12 months for a safe return (Gornitzky et al., 2016). Differences exist between amateur and professional athletes, with professionals benefiting from more intensive rehabilitation programs and personalized training regimens, leading to a slightly quicker return-to-sport timeline (Borges Sarmento et al., n.d.). However, professional athletes may also face greater psychological pressure to return, which can increase reinjury risks if premature.

4.3 Complications and Factors Affecting Surgical Success

The risk of ACL re-rupture is a major concern, particularly in young athletes engaged in pivoting and cutting sports. Studies report a re-rupture rate of 15-30% in athletes under 25 years old who return to high-risk sports (Barber-Westin & Noyes, 2020). Graft choice plays a crucial role in reinjury rates, with autografts demonstrating lower failure rates compared to allografts

(Sim et al., 2022). The type of graft used also influences recovery, with BPTB grafts associated with anterior knee pain and hamstring tendon grafts linked to residual muscle weakness (Ostojic et al., 2024). Rehabilitation is a critical determinant of long-term success, as inadequate rehabilitation increases the likelihood of graft failure and secondary knee injuries. Early-stage rehabilitation should emphasize range of motion and quadriceps activation, while later stages focus on strength, neuromuscular control, and sport-specific training to minimize reinjury risk (Fort-Vanmeerhaeghe et al., 2022).

Long-term complications following ACL reconstruction remain a significant concern, particularly for athletes returning to high-impact sports.

Osteoarthritis is one of the most prevalent long-term complications, with studies indicating that up to 50% of patients develop post-traumatic osteoarthritis within 12-14 years after surgery (Cheung et al., 2020). The development of osteoarthritis is influenced by multiple factors, including residual joint instability, meniscal damage, and altered knee biomechanics post-reconstruction. Recent research highlights that improper alignment of graft tunnels and residual rotational instability may contribute to early cartilage degeneration, emphasizing the need for precise surgical techniques (Andrä et al., 2021).

Psychological barriers, particularly fear of reinjury, significantly impact the success of ACL reconstruction and return-to-sport rates. Studies suggest that psychological readiness plays a crucial role in determining whether an athlete returns to their pre-injury level of competition (Ardern et al., 2013). Fear of reinjury and lack of confidence in knee stability can lead to movement compensations that increase the risk of secondary injuries (Paterno et al., 2018). Psychological interventions, such as cognitive-behavioral therapy and sport-specific mental training, have been proposed to enhance psychological resilience and improve return-to-play outcomes (Ardern et al., 2022).

5. Future of ACL Reconstruction – Research Directions

5.1 Biological and Regenerative Therapies

Advancements in biological treatments have opened new possibilities for improving ACL reconstruction outcomes. Platelet-rich plasma (PRP) and mesenchymal stem cells (MSCs) are increasingly used to enhance graft healing, reduce inflammation, and accelerate ligamentization. Studies indicate that PRP may improve tendon-to-bone integration by promoting angiogenesis and collagen deposition, although its efficacy remains inconsistent across clinical trials (Kunze et al., 2022). MSC-based therapies, particularly those derived from bone marrow and adipose tissue, show promise in promoting ligament regeneration and

improving biomechanical strength (Hexter et al., 2021; Yu et al., 2024). Future research aims to optimize delivery methods and assess long-term clinical benefits.

5.2 Artificial Intelligence in ACL Rehabilitation

Artificial intelligence (AI) and machine learning are being integrated into ACL rehabilitation programs to provide personalized recovery protocols. AI-driven motion analysis can identify compensatory movement patterns that increase reinjury risk, allowing for real-time feedback and adaptive training modifications (Schulc et al., 2024). Wearable sensors combined with AI-powered algorithms have been developed to track knee biomechanics and assess recovery progress, enabling clinicians to make data-driven decisions regarding return-to-sport readiness (Preatoni et al., 2022). As technology advances, AI has the potential to revolutionize rehabilitation strategies, improving both efficiency and patient outcomes.

5.3 Non-Surgical ACL Regeneration

Recent breakthroughs in regenerative medicine suggest that ACL healing without surgery may become a viable option. Research on scaffold-based tissue engineering aims to stimulate natural ligament healing through bioactive scaffolds seeded with growth factors and stem cells (Russo et al., 2022). The Bridge-Enhanced ACL Repair (BEAR) technique, which uses a bioactive scaffold to promote intrinsic ligament healing, has demonstrated encouraging early clinical results, showing comparable functional outcomes to traditional reconstruction (Murray et al., 2019). While these techniques are still in experimental stages, they offer promising alternatives for specific patient populations, particularly those with partial ACL tears or lower activity demands.

6. The Role of Rehabilitation After ACL Reconstruction in Athletes

6.1 Importance of Rehabilitation in Recovery

Rehabilitation following ACL reconstruction is a crucial component of recovery, influencing both functional outcomes and return-to-sport success. A well-structured rehabilitation program aims to restore knee stability, improve neuromuscular control, and minimize the risk of reinjury. Early rehabilitation focuses on reducing swelling, restoring knee range of motion, and initiating quadriceps activation, which plays a critical role in knee stability (Bousquet et al., 2018). As recovery progresses, the emphasis shifts toward strength training, proprioception exercises, and sport-specific drills to ensure the athlete regains confidence and functionality (Ball et al., 2018).

6.2 Phases of Rehabilitation

Rehabilitation typically follows a phased approach, beginning with the acute phase (0-6 weeks), where the primary goals are pain management, reduction of swelling, and regaining knee

mobility. This period includes passive range of motion exercises, quadriceps activation, and controlled weight-bearing activities (Piedade et al., 2023). The strengthening phase (6-12 weeks) emphasizes muscle strengthening, particularly the quadriceps and hamstrings, along with balance and coordination exercises to enhance neuromuscular control. The functional training phase (3-6 months) introduces plyometric exercises, agility drills, and progressive running programs tailored to the athlete's sport. Finally, the return-to-sport phase (6-12 months) incorporates high-intensity training, reactive drills, and a gradual return to competitive activities while ensuring psychological readiness and risk assessment using return-to-sport criteria (Webster et al., 2018).

6.3 Neuromuscular Training and Injury Prevention

Neuromuscular training plays a vital role in rehabilitation and reinjury prevention. Programs that focus on improving landing mechanics, cutting techniques, and hip-knee stability have been shown to reduce ACL reinjury rates by addressing movement deficiencies (Gokeler et al., 2013). Strength imbalances, particularly between the quadriceps and hamstrings, can contribute to altered biomechanics, increasing the risk of reinjury (Buckthorpe et al., 2019). Integrating neuromuscular training into rehabilitation protocols has been found to enhance proprioception, motor control, and joint stabilization, significantly improving long-term outcomes.

6.4 Psychological Aspects of Rehabilitation

Psychological readiness is a key determinant of successful return to sport. Many athletes experience fear of reinjury, anxiety, and reduced confidence in knee function following ACL reconstruction. Studies suggest that psychological barriers contribute to delayed return-to-sport timelines and increased reinjury risk (Hsu et al., 2017). Rehabilitation programs incorporating cognitive-behavioral strategies, mental imagery, and graded exposure to sport-specific activities help athletes rebuild confidence and improve return-to-play success rates (Coronado et al., 2020). Addressing psychological factors is essential to ensure that athletes do not return prematurely or adopt compensatory movement patterns that could predispose them to further injuries.

6.5 Criteria for Safe Return to Sport

Deciding when an athlete is ready to return to sport requires a comprehensive assessment of physical, functional, and psychological factors. Objective criteria, such as limb symmetry index (LSI >90%), functional hop tests, and isokinetic strength testing, are commonly used to evaluate an athlete's readiness (Paterno et al., 2022). Athletes who fail to meet these benchmarks have a significantly higher risk of reinjury. Additionally, psychological assessments and movement

analysis should be incorporated into return-to-play decisions to ensure that athletes are fully prepared for the demands of their sport.

7. Discussion

This systematic review highlights the complexity of ACL reconstruction and rehabilitation, emphasizing the multifactorial nature of surgical success, reinjury prevention, and return-to-sport outcomes. The findings underscore the importance of selecting an optimal graft type, implementing individualized rehabilitation protocols, and addressing psychological readiness to improve post-surgical outcomes in athletes.

The analysis of surgical techniques demonstrates that autografts, particularly bone-patellar tendon-bone (BPTB) and quadriceps tendon grafts, remain the preferred choices due to their superior biomechanical properties, faster integration, and lower failure rates compared to allografts and synthetic grafts. However, graft selection should be tailored to the athlete's sport-specific demands, anatomical factors, and risk of donor site morbidity. While allografts reduce surgical morbidity, they are associated with delayed biological incorporation and higher failure rates, particularly in younger, high-performance athletes. The increasing use of quadriceps tendon autografts suggests a promising alternative that balances strength, stability, and reduced donor-site complications. Further research should focus on long-term comparative outcomes of these grafts in elite athletes.

Rehabilitation remains a critical determinant of functional recovery and return to sport. Evidence suggests that structured, progressive rehabilitation protocols focusing on strength restoration, neuromuscular control, and sport-specific training improve functional outcomes and reduce reinjury risk. However, variability in rehabilitation protocols across studies presents challenges in standardizing best practices. Future research should explore the efficacy of objective return-to-play criteria, including isokinetic strength assessments, neuromuscular control evaluations, and psychological readiness screening, to ensure safe and effective return to competition.

A significant barrier to successful return to sport is the psychological aspect of recovery. Fear of reinjury, lack of confidence in knee stability, and psychological distress contribute to suboptimal return-to-sport rates, even in athletes with successful surgical and physical rehabilitation outcomes. Studies indicate that psychological readiness is a key predictor of return-to-sport success, suggesting that integrating psychological interventions, such as cognitive-behavioral therapy and graded exposure training, into rehabilitation programs may improve post-surgical outcomes.

Long-term complications, particularly post-traumatic osteoarthritis, remain a concern following ACL reconstruction. Despite advances in surgical precision and rehabilitation strategies, up to 50% of athletes develop osteoarthritis within 12-14 years post-surgery. This highlights the need for further research into graft biomechanics, joint-loading optimization, and regenerative treatments, such as biological augmentation with platelet-rich plasma (PRP) and mesenchymal stem cells (MSCs), to enhance graft healing and long-term knee health. Additionally, emerging technologies, including artificial intelligence-driven rehabilitation and wearable biomechanical tracking devices, offer promising solutions for monitoring recovery and preventing reinjury, warranting further exploration in future studies.

8. Conclusion

ACL reconstruction remains a cornerstone of sports medicine, with continuous advancements in surgical techniques, rehabilitation protocols, and injury prevention strategies. This review highlights the superiority of autografts in terms of biomechanical properties and success rates, the crucial role of structured rehabilitation, and the significant impact of psychological readiness on return-to-sport outcomes. Despite these advances, return-to-sport rates remain suboptimal, with a considerable risk of reinjury and long-term complications, such as osteoarthritis.

Future research should focus on standardizing rehabilitation protocols, integrating psychological interventions, and advancing regenerative medicine approaches to optimize ACL reconstruction outcomes. Additionally, technological innovations, such as AI-based rehabilitation tools and wearable sensors, hold potential for improving personalized rehabilitation and injury prevention. A multidisciplinary approach that combines surgical advancements, evidence-based rehabilitation, and psychological support will be essential in enhancing long-term functional recovery and return-to-sport success for athletes following ACL reconstruction.

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Authors' contributions

Conceptualization: SD, WK;

Methodology: SD, AB;

Software: n/a; check: SD, AB, WK;

Formal analysis: SD, AK, KSz;

Investigation: SD, AB, WK, AK, KSz;

Resources: SD, KSz, RT, MM;

Data curation: AB, WK, MM, AK, ABy;

Writing - rough preparation: SD, RT, KSz, Aby, WD;

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