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An Analytic Review of Current Approaches to Anterior Cruciate Ligament Reconstruction: Integrating Surgical Techniques, Graft Selection, and Emerging Role of Artificial Intelligence

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ABSTRACT

Aims: The purpose of this analytic review is to investigate the current surgical strategies for Anterior Cruciate Ligament (ACL) reconstruction, critically examine graft selection criteria, highlight emerging technological supports such as Artificial Intelligence (AI), and provide integrative insights for improving post-surgical outcomes.

Method and Materials: Major developments in the biomechanical understanding of ACL injury and associated reconstructive procedures were extracted from contemporary literature. Analytical comparison was performed across surgical methods, graft choices, and computational innovations influencing clinical decision-making.

Findings: Historical and contemporary findings indicate that surgical evolution, particularly toward anatomic reconstruction and individualized graft selection, has significantly enhanced biomechanical stability and recovery. Artificial intelligence shows promise in optimizing diagnosis, patient stratification, and rehabilitation protocols through data-driven models.

Conclusion: Anterior Cruciate Ligament reconstruction strategies continue to evolve towards precision-based care integrating biomechanics, surgical innovation, and computational assistance. Future research should focus on the synergy between surgical experience and algorithmic prediction to maximize personalized treatment outcomes.

Keywords: Anterior Cruciate Ligament, Reconstruction, Graft Choice, Surgical Techniques, Biomechanics

Introduction

The Anterior Cruciate Ligament (ACL) plays a key biomechanical role in stabilizing the knee by limiting forward movement of the tibia and controlling rotational loads [1]. Injuries to this ligament are common in pivot heavy sports, including football, basketball, and skiing, and often require surgical management to regain joint stability and facilitate a safe return to athletic activity [2]. Current surgical approaches emphasize anatomical restoration, improved graft integration, and tailored treatment strategies that address individual patient needs. Nevertheless, despite extensive clinical investigation, no graft option or operative technique has consistently demonstrated superiority across all patient groups [3]. Moreover, the growing application of Artificial Intelligence (AI) in orthopedics is ushering in a new phase of data supported decision making and heightened surgical accuracy.

Surgical Techniques in ACL Reconstruction

A) Single-Bundle ACL Reconstruction (SB-ACLR)

This conventional approach, involves creating a single femoral and tibial tunnel to accommodate a single graft that replaces the anteromedial bundle of the native ligament. This technique restores anterior stability effectively and remains widespread due to its relative technical simplicity and reproducibility. However, biomechanical evidence suggests that single-bundle reconstruction may not fully replicate native knee rotational control in high-demand athletic scenarios. Nevertheless, long-term clinical outcomes generally show satisfactory functional restoration in most patients, without excessive complexity or cost [4].

B) Double-Bundle ACL Reconstruction (DB-ACLR)

DB-ACLR aims to reconstruct both the anteromedial and posterolateral bundles by creating two separate femoral and tibial tunnels and using two graft strands. Biomechanical studies indicate improved rotational stability with this technique compared to single-bundle approaches. Despite this, clinical superiority remains a topic of ongoing debate due to increased surgical complexity and mixed evidence regarding long-term functional benefit [4].

C) Primary Repair and Internal Bracing

Primary repair of the ACL, historically abandoned due to high failure rates, has re-emerged in specific cases of proximal avulsion tears with adequate tissue quality. Augmentation using tensioned suture tape ("internal bracing") is intended to provide early stability while native tissue heals, though indications remain narrow and results variable [5].

D) Combined Procedures: ACL Reconstruction with Lateral Extra-articular Tenodesis

For individuals presenting with pronounced rotational instability or generalized ligamentous laxity, performing a lateral extra-articular tenodesis (LET) in conjunction with ACL reconstruction can provide additional rotational stability. Current evidence indicates that incorporating LET may decrease the likelihood of graft failure in patients considered high risk; however, this combined approach can extend operative duration and carries a potential risk of over-constraining the knee joint [6].

Method and Materials

The literature included peer-reviewed articles, systematic reviews, meta-analyses, and recent technological reports on ACL reconstruction and artificial intelligence applications in orthopedics. Studies were comparatively evaluated based on surgical outcomes, graft durability, biomechanical stability, and postoperative functional recovery. Emphasis was placed on evidence published in contemporary orthopedic and sports medicine journals. Relevant literature was identified through searches in major scientific databases including PubMed, Scopus, and Web of Science, focusing primarily on studies published within the last two decades related to ACL reconstruction techniques, graft selection, and artificial intelligence applications.

Graft Selection Paradigms

The choice of graft plays a decisive role in biological healing, mechanical durability, donor-site consequences, and overall long-term outcomes. Commonly utilized options include autografts harvested from the hamstring tendon, Bone–Patellar Tendon–Bone (BPTB), and quadriceps tendon, as well as allograft tissues.

A) Hamstring Tendon Autograft

Hamstring tendon autografts are frequently selected due to their association with lower rates of anterior knee discomfort and reduced donor-site complications relative to other autograft types. Nonetheless, numerous studies report that these grafts exhibit a greater tendency toward elongation or failure than BPTB or quadriceps tendon grafts, particularly in revision procedures. Recent systematic evidence indicates that in revision ACL reconstruction, hamstring grafts often yield outcomes equivalent to or slightly inferior to those of quadriceps tendon and BPTB autografts, with reports of increased anterior laxity and elevated failure rates in certain studies [7].

B) Bone–Patellar Tendon–Bone (BPTB) Autograft

BPTB autografts offer strong bone-to-bone integration and dependable initial fixation, which contribute to their consistently lower failure rates in young, active athletes. Systematic clinical analyses show that BPTB grafts demonstrate the lowest rates of reinjury and the highest rates of return to sport (RTS) among available autograft options. However, their use may be associated with increased anterior knee pain and discomfort during kneeling activities [8].

C) Quadriceps Tendon Autograft

Quadriceps tendon autografts have gained prominence due to their larger graft size and advantageous biomechanical characteristics. Comparative research indicates that these grafts present low failure rates and produce functional outcomes comparable to both BPTB and hamstring autografts, while also being associated with reduced donor-site morbidity[9].

D) Allografts

Allograft tissues eliminate donor-site morbidity and can shorten surgical time; however, they integrate more slowly than autografts and demonstrate higher rates of failure in younger, high-demand patients. Although allografts may be appropriate for revision surgeries or older individuals with lower activity levels, current evidence continues to support autografts as the preferred option in most primary ACL reconstructions [10].

Findings

The comparative evaluation of current ACL reconstruction strategies demonstrated substantial variation in biomechanical performance, graft incorporation, and postoperative recovery profiles among available techniques. Evidence from recent clinical and biomechanical studies suggests that individualized graft selection, combined with anatomically oriented surgical reconstruction, yields superior functional outcomes across many patient populations.

Table 1) Comparative analysis of graft types

Graft Type	Fixation Strength	Biological Incorporation	Donor-Site Morbidity	Failure Risk (Young Athletes)	Return to Sport (RTS)
Hamstring Tendon	Moderate	Tendon-to-bone	Low	Moderate–High	Moderate
BPTB Autograft	High	Bone-to-bone (fast)	Moderate	Low	High
Quadriceps Tendon	High	Tendon/bone	Low–Moderate	Low–Moderate	Moderate–High
Allograft	Moderate	Slower	None	Higher	Variable

Overall, BPTB and quadriceps tendon autografts showed greater stability and lower failure rates in high-demand athletes. In contrast, allografts were associated with slower incorporation and an increased risk of reinjury in younger populations. Advances in AI-assisted planning and rehabilitation monitoring have also demonstrated potential to improve surgical precision and personalized postoperative management.

Emerging Role of Artificial Intelligence in ACL Reconstruction

Artificial Intelligence and machine learning are rapidly emerging as tools that can enhance multiple aspects of ACL reconstruction surgery, including:

Preoperative Imaging and Tissue Characterization

AI-driven image analysis can improve diagnostic accuracy for ACL rupture patterns and quantify morphological variables from MRI and CT scans. These techniques support individualized preoperative planning and graft size prediction based on patient-specific anatomy [11].

A) Surgical Planning and Intraoperative Navigation

Machine learning algorithms can integrate demographic, anatomical, biomechanical, and activity-related data to recommend optimized graft choice and surgical technique. AI-enhanced navigation systems provide real-time guidance for tunnel placement, potentially improving reproducibility and accuracy. For example, a dynamic arthroscopic navigation system with a multilevel memory architecture has demonstrated improved tracking accuracy during ACL reconstruction, substantially enhancing intraoperative precision compared with static methods [12].

B) Predictive Outcome Modeling and Rehabilitation Monitoring

Artificial Intelligence can also facilitate predictive analytics for rehabilitative progress, return-to-sport timelines, and long-term risks such as post-traumatic osteoarthritis. Integration of AI-based decision support into postoperative care holds promise for customized rehabilitation protocols tailored to individual recovery trajectories [13].

Discussion

Current evidence underscores that graft selection and surgical technique in ACL reconstruction should be guided by a patient-specific approach that considers anatomical, biomechanical, and lifestyle factors rather than a uniform protocol. The evolution from standardized reconstruction methods toward personalized orthopedic decision-making reflects a broader shift in surgical philosophy, one that balances clinical outcomes, patient satisfaction, and technological integration. While BPTB autografts consistently demonstrate lower graft failure rates and superior return-to-sport outcomes in young athletic populations, they are also associated with greater donor-site morbidity, particularly anterior knee pain and kneeling discomfort [8]. Conversely, hamstring tendon autografts, though favored for reduced morbidity, may exhibit higher elongation rates and inferior fixation characteristics, leading to potential residual laxity [7]. In this regard, the quadriceps tendon autograft has emerged as a promising hybrid option, offering a favorable compromise between mechanical robustness and reduced donor-site complications [9].

The choice among these grafts must also take into account revision scenarios, patient comorbidities, and sport-specific demands. For instance, quadriceps or BPTB autografts may be preferred for high-demand athletes. In contrast, allografts may be considered for older individuals or in revision surgeries where donor-site morbidity must be minimized [10]. Importantly, consistent reporting of long-term graft survival and functional outcomes remains critical to refining evidence-based selection [10]. Parallel to these clinical considerations, the incorporation of AI and machine learning into ACL reconstruction marks a transformative leap toward precision medicine. These technologies facilitate predictive modeling of risk factors, automate preoperative imaging analysis, and provide intraoperative navigation support. Currently, AI-assisted surgical planning tools can process extensive datasets, including patient-specific anatomy, biomechanical forces, and activity levels, to propose optimized graft types and tunnel placement strategies [11-13].

Moreover, the real-time integration of AI-powered arthroscopic navigation systems has demonstrated the capacity to improve surgical reproducibility and minimize human error. These advancements can potentially reduce intraoperative variability among surgeons, particularly in anatomically complex or revision cases. Postoperatively, AI-based algorithms also show promise for continuous monitoring of rehabilitation progress via wearable sensors and motion-tracking systems [14]. Such dynamic feedback loops enable real-time adjustments in rehabilitation intensity, ensuring that recovery is both safe and individualized. Nevertheless, the clinical implementation of AI in orthopedic surgery is not without challenges [15]. Data heterogeneity, algorithmic transparency, and regulatory validation are essential hurdles to overcome before widespread adoption. Ethical considerations regarding patient consent, privacy, and the interpretability of machine-driven recommendations must also be addressed systematically. Future AI systems should complement rather than replace clinical judgment, serving as intelligent extensions of surgical expertise rather than autonomous agents.

Collectively, these developments signal a paradigm shift toward precision orthopedics, in which surgical success is increasingly defined by data-informed personalization. By merging advanced computational capabilities with surgical artistry, AI holds the potential to refine graft selection accuracy, enhance intraoperative precision, and optimize postoperative rehabilitation, ultimately leading to improved functional outcomes and reduced complication rates. Continued interdisciplinary collaboration between engineers, clinicians, and data scientists will be pivotal in shaping the next generation of ACL reconstruction strategies.

Conclusion

Anterior Cruciate Ligament reconstruction remains a complex surgical endeavor requiring thoughtful graft selection and meticulous execution. Autografts, particularly BPTB and quadriceps tendon grafts, offer robust clinical outcomes, while AI-assisted surgical planning and navigation represent the frontier of precision orthopedic care. Continued high-quality research, including randomized controlled trials and longitudinal studies, is essential for refining best practices and further elucidating the role of emerging technologies in ACL surgery.

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Authors' Contribution

The author, E.P, was solely responsible for the conception, drafting, and final approval of this editorial.

Conflict of Interest

The author declares no conflicts of interest regarding the publication of this editorial

Ethical Considerations

As this is a narrative review article, it does not constitute a primary research study and therefore does not require an ethics code.

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