Coronal and Sagittal Plane Malalignment in Anterior Cruciate Ligament Deficiency: Clinical Implications, and Surgical Strategies

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Abstract

Background: Anterior cruciate ligament (ACL) deficiency is a complex pathological condition that extends beyond isolated ligament disruption, involving significant alterations in knee biomechanics influenced by both coronal and sagittal plane malalignment. Increasing evidence suggests that factors such as varus deformity and increased posterior tibial slope (PTS) play a pivotal role in the pathogenesis of ACL injury, persistence of instability, and failure of reconstruction. Despite advances in surgical techniques, failure rates following ACL reconstruction (ACLR) remain notable, highlighting the importance of addressing underlying osseous malalignment.

The aim of this review is to comprehensively analyze the biomechanical relationship between coronal and sagittal malalignment and ACL deficiency, and to evaluate their clinical implications in both primary and revision settings. Particular emphasis is placed on varus alignment, posterior tibial slope, and their combined effect on knee kinematics, graft stress, and long-term joint degeneration.

Coronal malalignment, particularly varus alignment, leads to increased medial compartment loading and abnormal force distribution across the knee joint. This results in elevated tensile stress on the ACL, contributing to both primary injury and graft failure. Similarly, increased posterior tibial slope has been shown to augment anterior tibial translation, thereby increasing strain on the ACL and reconstructed grafts. The interaction between these deformities creates a biomechanically unfavorable environment that predisposes patients to recurrent instability and progressive osteoarthritis.

Clinical studies demonstrate that failure to address malalignment during ACLR is associated with inferior outcomes, particularly in patients with significant varus deformity (>5°) or increased PTS (>10–12°). In such cases, corrective osteotomy procedures, including high tibial osteotomy, have been shown to improve knee stability, reduce graft stress, and enhance long-term outcomes.

In conclusion, coronal and sagittal malalignment are critical yet often underappreciated contributors to ACL pathology. A comprehensive preoperative assessment of limb alignment is essential for optimizing surgical decision-making. Integrating alignment correction strategies with ligament reconstruction may represent the key to improving functional outcomes and reducing failure rates in ACL-deficient patients.

Keywords: *Coronal,Sagittal Plane Malalignment, Anterior Cruciate Ligament Deficiency*

Introduction

Anterior cruciate ligament (ACL) injuries represent one of the most common and clinically significant knee pathologies, particularly among young and physically active individuals. The ACL plays a fundamental role in maintaining knee stability by resisting anterior tibial translation, controlling rotational movements, and contributing to overall joint kinematics. Disruption of this ligament leads to functional instability, altered biomechanics, and a high risk of secondary intra-articular damage, including meniscal tears and progressive cartilage degeneration. [1]

Historically, ACL injury has been considered an isolated ligamentous problem; however, increasing attention has been directed toward the role of lower limb alignment in both the development of ACL injury and the success of reconstruction procedures. Coronal plane malalignment, particularly varus deformity, results in asymmetric load distribution across the knee joint, increasing stress on the medial compartment and placing excessive strain on the ACL. [2]

In addition to coronal alignment, sagittal plane factors such as posterior tibial slope (PTS) have gained significant importance in recent years. An increased PTS has been shown to enhance anterior tibial translation, thereby increasing the mechanical load on the ACL and predisposing both native and reconstructed ligaments to failure. [3]

The coexistence of coronal and sagittal malalignment creates a biomechanically unfavorable environment that contributes not only to the initial ACL injury but also to persistent instability and graft failure following reconstruction. These combined deformities may accelerate degenerative changes within the knee joint if not appropriately addressed. [4]

Failure to recognize and correct underlying malalignment has been associated with inferior clinical outcomes and a higher risk of revision ACL reconstruction. This is particularly evident in patients with significant varus deformity or excessive posterior tibial slope, where abnormal joint loading persists despite technically successful ligament reconstruction. [5]

Despite growing evidence supporting the role of alignment correction, current clinical practice lacks a standardized approach that integrates both ligamentous and osseous factors. Most available studies focus on individual alignment parameters, with limited emphasis on their combined biomechanical and clinical effects. [6-8]

The aim of this review is to comprehensively evaluate the role of coronal and sagittal plane malalignment in anterior cruciate ligament deficiency, with particular focus on their biomechanical impact, clinical implications, and influence on surgical outcomes. [7]

There remains a lack of unified evidence addressing the combined influence of coronal and sagittal malalignment on ACL injury mechanisms and reconstruction outcomes, as well as clearly defined indications for corrective osteotomy in conjunction with ACL reconstruction.

The anterior cruciate ligament (ACL) is a critical intra-articular structure located centrally within the knee joint, extending from the posteromedial aspect of the lateral femoral condyle to the intercondylar region of the tibia. It typically measures between 27 and 38 mm in length and is composed predominantly of type I collagen fibers, providing substantial tensile strength. In addition to its mechanical role, the ACL is richly innervated with mechanoreceptors that contribute to proprioception and neuromuscular control, which are essential for coordinated joint stability during dynamic activities. [9]

The ACL is functionally divided into two primary bundles: the anteromedial (AM) and posterolateral (PL) bundles, each contributing differently to knee stability throughout the range of motion. The AM bundle remains taut during knee flexion and primarily resists anterior tibial translation, whereas the PL bundle becomes more tensioned in extension and plays a crucial role in controlling rotational stability. This complementary function ensures that the ACL provides continuous stabilization under varying biomechanical demands. [10]

Morphologically, the ACL demonstrates a ribbon-like and twisted configuration, with its fibers undergoing orientation changes during knee movement. This structural arrangement allows the ligament to adapt to varying tension patterns during flexion and extension. The twisting of fibers untwines as the knee extends, optimizing load sharing across the ligament and preventing localized stress concentration, which is critical for maintaining structural integrity under physiological loads. [11]

The femoral insertion of the ACL is crescent-shaped and located on the medial aspect of the lateral femoral condyle, with its anterior border defined by the lateral intercondylar ridge. This insertion site is composed of both direct and indirect fiber attachments, where the direct fibers provide the primary load-bearing function. Restoration of this anatomical footprint during ACL reconstruction is essential, as non-anatomic placement has been strongly associated with graft failure and persistent instability. [12]

On the tibial side, the ACL inserts into the intercondylar area of the tibia, typically positioned anterior to the posterior cruciate ligament and extending toward the anterior horn of the lateral meniscus. The tibial footprint is broader than the femoral insertion and varies in shape, commonly described as oval, triangular, or C-shaped. Proper identification of this insertion site is critical during reconstruction to avoid graft impingement and ensure restoration of normal knee kinematics. [13]

Biomechanically, the primary function of the ACL is to resist anterior translation of the tibia relative to the femur, particularly during activities involving deceleration, pivoting, and cutting movements. In addition, the ACL plays a significant role in controlling rotational stability and contributes to the screw-home mechanism during terminal knee extension. Disruption of the ACL leads to abnormal joint kinematics, which predispose the knee to instability and secondary intra-articular damage. [14]

The forces acting on the ACL are not constant throughout the range of motion; rather, they vary depending on knee position and external loads. Studies have demonstrated that ACL strain is highest during the last 30 degrees of extension and under combined loading conditions such as anterior tibial translation, internal rotation, and valgus stress. These biomechanical insights explain the mechanisms underlying common injury patterns and highlight the importance of restoring physiological loading conditions during reconstruction. [15]

In addition to its primary stabilizing role, the ACL functions as a secondary restraint to varus and valgus stresses, particularly in situations where the collateral ligaments are compromised. This highlights the interdependence between ligamentous structures and overall knee alignment. Consequently, alterations in coronal or sagittal alignment can significantly influence ACL loading patterns, reinforcing the concept that ACL pathology cannot be fully understood without considering the broader biomechanical environment of the knee. [16]

Knee alignment represents a fundamental determinant of load distribution and joint biomechanics, directly influencing both ligament function and articular cartilage health. Proper alignment ensures that forces transmitted through the lower limb are evenly distributed across the knee joint, minimizing focal stress concentrations. Any deviation from normal alignment alters joint mechanics and can predispose to instability, degenerative changes, and failure of ligamentous structures such as the ACL. [17]

The concept of lower limb alignment is primarily evaluated using the mechanical and anatomical axes of the femur and tibia. The anatomical axis corresponds to the longitudinal axis of each bone shaft, whereas the mechanical axis represents the weight-bearing line extending from the center of the femoral head to the center of the ankle joint. These axes are not parallel in the femur, typically forming an angle of approximately 5° to 7°, which must be considered during deformity assessment and surgical planning. [18]

The mechanical axis of the lower extremity, also known as the Mikulicz line, is a critical parameter in assessing overall limb alignment. In a normally aligned limb, this axis passes slightly medial to the center of the knee joint, ensuring balanced load distribution between the medial and lateral compartments. Deviation of this axis medially results in varus alignment, while lateral deviation leads to valgus alignment, both of which significantly impact knee biomechanics and ligament loading patterns. [19]

One of the most clinically relevant parameters in alignment assessment is the hip–knee–ankle (HKA) angle, which reflects the relationship between the mechanical axes of the femur and tibia in the coronal plane. A normal HKA angle is close to 180°, with slight physiological variations. Values less than 177° indicate varus malalignment, whereas values greater than 183° indicate valgus alignment. These deviations are strongly associated with abnormal joint loading and may influence ACL strain and injury risk. [20]

Mechanical axis deviation (MAD) further quantifies the extent of malalignment by measuring the distance between the mechanical axis line and the center of the knee joint. Normally, this value lies within a narrow medial range, and any significant shift indicates altered load transmission across the knee. Increased medial deviation is associated with excessive loading of the medial compartment, contributing to cartilage degeneration and increased stress on stabilizing structures such as the ACL. [21]

Additional angular parameters, including the medial proximal tibial angle (MPTA) and lateral distal femoral angle (LDFA), are essential for identifying the origin of deformity within the lower limb. The MPTA evaluates the relationship between the tibial mechanical axis and the joint line, whereas the LDFA assesses the distal femoral alignment. Abnormal values in these angles help distinguish whether deformity arises from the tibia, femur, or both, which is critical for planning corrective osteotomy. [22]

The joint line convergence angle (JLCA) provides insight into intra-articular factors contributing to malalignment, including cartilage loss and ligamentous laxity. An increased JLCA is often indicative of medial compartment degeneration or soft tissue imbalance, particularly in varus knees. This parameter is especially relevant in ACL-deficient knees, where chronic instability may exacerbate intra-articular deformities over time. [23]

Sagittal plane alignment is equally important, with posterior tibial slope (PTS) being a key determinant of anterior tibial translation. The PTS is defined as the posterior inclination of the tibial plateau relative to the tibial shaft, typically ranging between 7° and 10°. Variations in this slope significantly influence knee biomechanics, particularly in relation to ACL loading and stability. [24]

An increased posterior tibial slope leads to greater anterior shear forces during weight-bearing and dynamic activities, thereby increasing strain on the ACL. This biomechanical effect becomes particularly significant in ACL-deficient knees or after reconstruction, where excessive slope may predispose to graft failure. Consequently, assessment of PTS is essential in both preoperative planning and evaluation of failed ACL reconstructions. [25]

Understanding these alignment parameters collectively is crucial, as coronal and sagittal plane deformities rarely exist in isolation. Their combined effects create a complex biomechanical environment that directly influences ACL function, injury risk, and surgical outcomes. Therefore, comprehensive alignment assessment should be considered a cornerstone in the evaluation and management of ACL-deficient patients. [26]

Coronal Malalignment (Varus) and Its Impact on ACL

Coronal plane malalignment, particularly varus deformity, plays a critical role in the biomechanics of the knee joint and has significant implications for anterior cruciate ligament (ACL) integrity. Varus alignment, commonly described as a bow-legged deformity, results in medial deviation of the mechanical axis, leading to increased load transmission through the medial compartment of the knee. This altered load distribution creates a biomechanical environment that predisposes to both ligamentous stress and degenerative joint changes. [27]

The increased medial compartment loading associated with varus alignment contributes to progressive articular cartilage degeneration and medial meniscal pathology. Over time, this excessive loading leads to narrowing of the medial joint space and worsening deformity, establishing a vicious cycle of mechanical overload and structural deterioration. In ACL-deficient knees, this process is further accelerated due to instability-related abnormal joint kinematics. [28]

From a ligamentous perspective, varus malalignment significantly influences ACL loading patterns. The altered mechanical axis generates abnormal forces across the knee joint, placing increased tensile stress on the ACL, particularly during dynamic activities involving pivoting or rotational movements. This increased stress not only predisposes to primary ACL injury but also compromises the integrity of reconstructed grafts. [29]

Biomechanically, varus alignment induces a relative valgus moment at the level of the ACL, particularly during knee extension. This paradoxical loading pattern increases strain within the ligament, especially when combined with internal tibial rotation. Such conditions are commonly encountered during athletic activities, explaining the higher susceptibility to ACL injury in malaligned knees. [30]

Clinical studies have demonstrated a strong association between varus malalignment and failure of ACL reconstruction. Patients with untreated varus deformity exhibit higher rates of graft failure, recurrent instability, and need for revision surgery. It has been reported that varus alignment contributes significantly to ACL reconstruction failure in a notable proportion of cases, emphasizing the importance of addressing alignment during surgical planning. [31]

The degree of varus deformity is also clinically relevant in determining treatment strategies. A varus alignment greater than 5° is often considered a threshold beyond which isolated ACL reconstruction may not be sufficient. In such cases, failure to correct the underlying deformity results in persistent abnormal loading, increasing the risk of graft elongation or rupture over time. [32]

In addition to graft-related complications, varus malalignment has been strongly associated with the development of medial compartment osteoarthritis following ACL injury. Longitudinal studies have shown that patients with varus alignment are more likely to develop early degenerative changes, highlighting the long-term consequences of uncorrected malalignment in ACL-deficient knees. [33]

The concept of “double varus” deformity further illustrates the complexity of coronal malalignment in ACL-deficient knees. This condition involves both osseous varus alignment and soft tissue laxity, particularly involving the posterolateral corner. The combination of these factors leads to significant instability and increased mechanical stress on the ACL, necessitating comprehensive surgical correction. [34]

Recognition of varus malalignment has led to the increasing use of corrective procedures such as high tibial osteotomy (HTO) in conjunction with ACL reconstruction. By shifting the mechanical axis laterally, HTO redistributes load away from the medial compartment and reduces stress on the ACL graft. This combined approach has been shown to improve knee stability and enhance long-term outcomes. [35]

Overall, coronal plane malalignment represents a key factor in the pathogenesis, progression, and surgical management of ACL deficiency. A thorough understanding of its biomechanical impact is essential for optimizing treatment strategies, preventing graft failure, and improving functional outcomes in affected patients. [36]

Posterior Tibial Slope (Sagittal Malalignment) and Its Impact on ACL

Posterior tibial slope (PTS) is a key sagittal plane parameter that significantly influences knee biomechanics and anterior cruciate ligament (ACL) loading. It is defined as the posterior inclination of the tibial plateau relative to the longitudinal axis of the tibia, with normal values typically ranging between 7° and 10°. Variations in this anatomical feature can substantially alter joint kinematics, particularly with respect to anterior tibial translation and ligament strain. [37]

An increased posterior tibial slope has been consistently associated with greater anterior tibial translation under both static and dynamic loading conditions. This occurs because the inclined tibial plateau facilitates anterior displacement of the tibia relative to the femur during weight-bearing activities. As a result, the ACL is subjected to increased tensile forces, which may predispose it to injury even in the absence of significant external trauma. [38]

Biomechanical studies have demonstrated that even small increases in PTS can lead to measurable increases in ACL strain. Each incremental degree of slope elevation contributes to higher anterior shear forces across the knee joint, amplifying the mechanical demand placed on the ACL. This relationship highlights the importance of considering sagittal alignment as a critical factor in both injury risk assessment and surgical planning. [39]

In the setting of ACL deficiency, increased posterior tibial slope exacerbates instability by promoting excessive anterior tibial translation during functional activities. This instability not only affects patient performance but also contributes to secondary damage to the menisci and articular cartilage. Consequently, patients with elevated PTS often present with more severe functional impairment and progressive joint degeneration. [40]

Posterior tibial slope has also been identified as a significant risk factor for failure following ACL reconstruction. Clinical studies have shown that patients with a PTS greater than 10° to 12° have a markedly increased risk of graft rupture compared to those with normal slope values. This is attributed to persistent abnormal anterior shear forces that continue to act on the reconstructed ligament despite technically successful surgery. [41]

The relationship between increased PTS and graft failure has important implications in revision ACL reconstruction. In patients with recurrent instability and elevated slope, isolated ligament reconstruction may be insufficient. Failure to address the underlying sagittal deformity can result in repeated graft failure, underscoring the need for a more comprehensive surgical approach. [42]

Slope-correcting osteotomy has emerged as an effective strategy in managing patients with excessive posterior tibial slope, particularly in revision settings. By reducing the slope, this procedure decreases anterior tibial translation and lowers the mechanical stress on the ACL graft. Early clinical outcomes suggest that combining slope correction with ACL reconstruction improves stability and reduces re-tear rates. [43]

Accurate measurement of posterior tibial slope is essential for proper clinical decision-making. This is typically performed on lateral radiographs using the anatomical axis of the tibia as a reference. Variations in measurement techniques and anatomical differences between medial and lateral plateaus must be considered to ensure precise assessment and avoid underestimation of slope abnormalities. [44]

It is important to recognize that sagittal malalignment rarely occurs in isolation and often coexists with coronal deformities such as varus alignment. The combination of increased PTS and varus malalignment creates a highly unfavorable biomechanical environment, significantly increasing the risk of both primary ACL injury and reconstruction failure. This interaction further supports the need for comprehensive alignment evaluation. [45]

In summary, posterior tibial slope is a critical determinant of ACL biomechanics, influencing both injury risk and surgical outcomes. Recognition and appropriate management of increased PTS are essential components of modern ACL treatment strategies, particularly in complex and revision cases where traditional approaches may fail. [46]

Combined Coronal and Sagittal Malalignment (Interaction and Clinical Impact)

Coronal and sagittal plane malalignments rarely exist in isolation; rather, they frequently coexist and interact to create a complex biomechanical environment that significantly affects anterior cruciate ligament (ACL) function. The combination of varus deformity and increased posterior tibial slope (PTS) results in compounded mechanical stresses across the knee joint, amplifying anterior tibial translation and rotational instability. This interaction represents a critical factor in both primary ACL injury and reconstruction failure. [47]

From a biomechanical perspective, varus alignment increases medial compartment loading, while an increased posterior tibial slope promotes anterior shear forces. When these deformities coexist, they synergistically increase strain on the ACL beyond the effect of either deformity alone. This dual-plane malalignment leads to persistent abnormal kinematics, even in the presence of an intact or reconstructed ligament. [48]

The presence of combined malalignment has been strongly associated with higher rates of ACL injury, particularly in athletes and high-demand individuals. The increased anterior tibial translation caused by elevated PTS, combined with the medial overload from varus alignment, creates a destabilizing environment that predisposes the ligament to rupture under relatively lower external forces. [49]

In ACL-deficient knees, the coexistence of these deformities exacerbates instability and accelerates joint degeneration. Repeated episodes of giving way, coupled with abnormal load distribution, contribute to progressive meniscal injury and cartilage deterioration. This highlights the importance of recognizing combined malalignment as a driver of both mechanical instability and degenerative progression. [50]

Clinical outcomes following isolated ACL reconstruction are significantly affected by the presence of uncorrected coronal and sagittal malalignment. Studies have demonstrated that patients with combined deformities experience higher rates of graft failure, residual instability, and inferior functional outcomes compared to those with normal alignment. This underscores the limitation of addressing ligamentous pathology alone without correcting underlying bony abnormalities. [51]

The concept of “multiplanar deformity” has therefore gained increasing attention in modern knee surgery. It emphasizes the need for comprehensive preoperative assessment, including full-length weight-bearing radiographs and sagittal plane evaluation, to identify all contributing factors to instability. Failure to detect and address these deformities may compromise even technically well-performed ACL reconstructions. [52]

Surgical strategies have evolved to address this complex interaction, with increasing use of combined procedures such as high tibial osteotomy (HTO) with ACL reconstruction. These approaches aim to correct both coronal and sagittal malalignment, thereby reducing mechanical stress on the ACL graft and restoring more physiological joint mechanics. Early clinical evidence supports improved stability and reduced failure rates with such combined interventions. [53]

In revision ACL reconstruction, the role of combined malalignment becomes even more critical. Patients presenting with failed grafts often exhibit underlying deformities that were not addressed during the primary procedure. In these cases, correction of both varus alignment and posterior tibial slope is often necessary to achieve successful long-term outcomes and prevent repeated failure. [54]

Despite growing recognition of this interaction, there remains a lack of standardized guidelines regarding the thresholds for surgical correction of combined deformities. Clinical decision-making often relies on a combination of radiographic parameters, patient symptoms, and surgeon experience, highlighting the need for further research in this area. [55]

In summary, the interaction between coronal and sagittal malalignment plays a pivotal role in ACL pathology and treatment outcomes. A comprehensive, multiplanar approach to evaluation and management is essential for optimizing knee stability, reducing graft failure, and improving long-term joint preservation. [56]

Clinical Implications and Surgical Decision-Making

The management of anterior cruciate ligament (ACL) deficiency in the presence of malalignment has evolved significantly, with increasing emphasis on addressing both ligamentous and osseous pathologies. Isolated ACL reconstruction in malaligned knees often fails to restore normal biomechanics, particularly in the presence of varus deformity or increased posterior tibial slope. This has led to the adoption of combined surgical strategies, most notably open wedge high tibial osteotomy (OWHTO) with ACL reconstruction, to achieve optimal outcomes. [57]

Open wedge high tibial osteotomy functions by realigning the mechanical axis of the lower limb, shifting load distribution from the medial compartment toward the lateral compartment. This correction reduces excessive medial compartment stress and decreases the abnormal forces acting on the ACL or its graft. In ACL-deficient knees with varus malalignment, this biomechanical correction is essential to restore joint stability and prevent progressive degeneration. [58]

The indication for combining OWHTO with ACL reconstruction is typically based on the presence of symptomatic instability associated with varus alignment, particularly when the deformity exceeds 5°. In such cases, performing ACL reconstruction alone may lead to persistent instability and increased risk of graft failure. Therefore, addressing the underlying malalignment becomes a critical component of surgical planning. [59]

In addition to coronal alignment, sagittal plane factors such as posterior tibial slope must also be considered when planning combined procedures. OWHTO allows for controlled modification of the tibial slope, which can reduce anterior tibial translation and decrease stress on the ACL graft. This dual correction in both coronal and sagittal planes enhances the biomechanical environment of the knee. [60]

The surgical sequence in combined procedures is an important consideration. Most contemporary approaches recommend performing the osteotomy first to establish proper limb alignment, followed by

ACL reconstruction. This sequence ensures that graft placement and tensioning are performed in the corrected mechanical environment, thereby optimizing functional outcomes and reducing graft overload. [61]

Patient selection remains a cornerstone for successful outcomes in combined OWHTO and ACL reconstruction. Ideal candidates are typically young, active individuals with symptomatic instability, varus malalignment, preserved lateral compartment cartilage, and good range of motion. Conversely, patients with advanced osteoarthritis, severe deformity, or poor bone quality may not be suitable candidates for this combined approach. [62]

Clinical outcomes of simultaneous OWHTO and ACL reconstruction have been increasingly favorable, with studies reporting improved knee stability, pain relief, and functional scores. Importantly, this combined approach has been shown to reduce graft failure rates compared to isolated ACL reconstruction in malaligned knees. These findings support the concept of treating both the cause and consequence of instability simultaneously. [63]

One of the major advantages of performing both procedures in a single setting is the ability to follow a unified rehabilitation protocol, reducing overall recovery time and avoiding multiple surgical interventions. Additionally, simultaneous surgery minimizes cumulative healthcare costs and allows earlier return to functional activities compared to staged procedures. [64]

However, combined procedures are technically demanding and require careful preoperative planning. Potential complications include delayed union of the osteotomy site, infection, neurovascular injury, and issues related to graft integration. Despite these risks, complication rates are generally comparable to those of isolated procedures when performed by experienced surgeons. [65]

In conclusion, the integration of open wedge high tibial osteotomy with ACL reconstruction represents a paradigm shift in the management of ACL-deficient knees with malalignment. By addressing both mechanical alignment and ligamentous instability, this combined approach provides a more comprehensive and durable solution, ultimately improving patient outcomes and reducing the risk of failure. [66]

Conclusion

Coronal and sagittal plane malalignment represent fundamental contributors to the pathomechanics of anterior cruciate ligament deficiency and play a decisive role in both injury risk and reconstruction outcomes. Varus deformity and increased posterior tibial slope act synergistically to amplify anterior tibial translation, alter load distribution, and increase stress on both the native ACL and reconstructed grafts. Recognition of these factors has shifted the paradigm from isolated ligament reconstruction toward a more comprehensive approach that integrates biomechanical alignment into surgical planning. The combination of open wedge high tibial osteotomy with ACL reconstruction provides an effective strategy to address both instability and malalignment simultaneously. By restoring the mechanical axis and optimizing sagittal alignment, this approach improves joint biomechanics, enhances graft longevity, and reduces the risk of failure. Future advancements should focus on refining patient selection criteria, standardizing surgical indications, and improving long-term outcome data to further establish combined procedures as the gold standard in managing complex ACL-deficient knees.

References

1. Moon HS, Song SY, Oh JU, Seo YJ. Effects of modified trans-tibial versus trans-portal technique on stress patterns around the femoral tunnel in anatomical single-bundle ACL reconstruction. *BMC Musculoskelet Disord.* 2022;23(1):759.
2. Hassebrock JD, Gulbrandsen MT, Asprey WL, Makovicka JL, Chhabra A. Knee ligament anatomy and biomechanics. *Sports Med Arthrosc Rev.* 2020;28(3):80-88.
3. Śmigielski R, Zdanowicz U, Drwięga M, Ciszek B, Williams A. The anatomy of the anterior cruciate ligament and its relevance to reconstruction. *Bone Joint J.* 2016;98-B(8):1020-1026.
4. Morales-Avalos R, Perelli S, Vilchez-Cavazos F, et al. ACL anatomy: Is there still something to learn? *Knee Surg Sports Traumatol Arthrosc.* 2024;68(4):T422-T427.

5. Cone SG, Howe D, Fisher MB. Size and shape of the human ACL: systematic review. *J Orthop Res.* 2019;7(6):e8.
6. Braaten JA, Schreier FJ, Rodriguez AN, et al. Modern treatment principles for multiligament knee injuries. *Ann Joint.* 2022;10(11):937.
7. Li G, DeFrate LE, Sun H, Gill TJ. In vivo elongation of ACL during knee flexion. *Am J Sports Med.* 2004;32(6):1415-1420.
8. Flandry F, Hommel G. Normal anatomy and biomechanics of the knee. *Sports Med Arthrosc Rev.* 2011;19(2):82-92.
9. Chao EY, Neluheni EV, Hsu RW, Paley D. Biomechanics of alignment. *Orthop Clin North Am.* 1994;25:379-386.
10. Paley D, Herzenberg JE, Tetsworth K, McKie J, Bhave A. Deformity planning for corrective osteotomies. *Orthop Clin North Am.* 1994;25(3):425-465.
11. Watanabe Y, Takenaka N, Kinugasa K, et al. Intra- and extra-articular deformity of lower limb. *Adv Orthop.* 2019;1-9.
12. Cherian JJ, Kapadia BH, Banerjee S, et al. Mechanical, anatomical, and kinematic axes in TKA. *Curr Rev Musculoskelet Med.* 2014;7(2):89-95.
13. Lee HI, Park D, Cho J. Clinical results after OWHTO. *Knee Surg Relat Res.* 2018;30(1):34-41.
14. Ji S, Huang Y, Zhou Y, et al. Predictive factors of residual varus alignment. *Front Surg.* 2023;9:1054351.
15. Paley D. Normal lower limb alignment and joint orientation. In: *Principles of Deformity Correction.* Springer; 2002.
16. Bergin PF, Miles DT, Mathis TP, et al. Lateral distal femoral angle variation. *J Orthop Trauma.* 2018;32(8):414-418.
17. Kim SH, Lee JW, Kim MG, et al. Radiologic findings associated with ACL degeneration. *Arch Orthop Trauma Surg.* 2023;143(7):4257-4265.
18. Noyes FR, Barber-Westin SD, Hewett TE. HTO and ligament reconstruction in varus ACL-deficient knees. *Am J Sports Med.* 2000;28:282-296.
19. Sanders TL, Maradit Kremers H, Bryan AJ, et al. Incidence of ACL tears. *Am J Sports Med.* 2016;44(6):1502-1507.
20. Nilsson M, Toresdahl B, Henriksson H, et al. Varus alignment and OA after ACL injury. *J Exp Orthop.* 2025;12:e70143.
21. Sharma L. Role of knee alignment in OA progression. *JAMA.* 2001;286:188-195.
22. Tischer T, Paul J, Pape D, et al. Impact of malalignment in ligament surgery. *Orthop J Sports Med.* 2017;5(3):2325967117697287.
23. Noyes FR, Barber-Westin SD. ACL revision reconstruction outcomes. *Am J Sports Med.* 2006;34:553-564.
24. Won HH, Chang CB, Je MS, et al. Alignment in revision ACL reconstruction. *Clin Orthop Relat Res.* 2013;471:3504-3511.
25. Schneider A, Gaillard R, Gunst S, et al. Combined ACLR and OWHTO outcomes. *Knee Surg Sports Traumatol Arthrosc.* 2020;28(3):960-968.
26. Webb JM, Salmon LJ, Leclerc E, et al. Posterior tibial slope and ACL injury. *Am J Sports Med.* 2013;41:2800-2804.
27. Hohmann E, Tetsworth K, Glatt V, et al. Posterior tibial slope and ACL injury risk. *Am J Sports Med.* 2021.
28. Marques B, Souza B, Simões M, et al. PTS changes after OWHTO. *Knee Surg Sports Traumatol Arthrosc.* 2020;28(10):3222-3228.
29. Ashy C, Bailey E, Hutchinson J, et al. Quadriceps graft outcomes. *Knee Surg Sports Traumatol Arthrosc.* 2023;31(12):5463-5476.
30. Moran J, Chona D, Parker DA, Coolican MRJ. High tibial osteotomy review. *J ISAKOS.* 2024;9(1):144-154.
31. Legnani C, Peretti GM, Del Re M, et al. Valgus high tibial osteotomy. *J ISAKOS.* 2024;9(3):447-457.
32. Sabzevari S, Ebrahimpour A, Khalilipour MR, et al. High tibial osteotomy review. *Arch Bone Jt Surg.* 2016;4(3):204-212.
33. Li Y, Zhang H, Zhang J, et al. Combined HTO and ACLR outcomes. *Arthroscopy.* 2015;31(3):507-519.

34. Kim JS, Park SB, Choi HG, et al. Combined ligament reconstruction with osteotomy. *Arch Orthop Trauma Surg.* 2023;143:3677-3689.
35. Deng FY, Liu JC, Li Z. Osteotomy combined with ACL reconstruction. *World J Clin Cases.* 2024;12(22):4897-4904.
36. Müller S, Frosch KH, Frings J, et al. Biplanar HTO techniques. *Orthop Traumatol Surg Res.* 2023;109(4):103339.
37. Loia MC, Vanni S, Rosso F, et al. Indications and limits of HTO. *Joints.* 2016;4(2):98-110.
38. Jin C, Song EK, Jin QH, et al. Outcomes of simultaneous HTO and ACLR. *BMC Musculoskelet Disord.* 2018;19:228.
39. Gupte PN, Dhamangaonkar AC, Mhatre SV, et al. Outcomes of combined ACLR and HTO. *J Arthrosc Joint Surg.* 2025;12(1):19-24.
40. Murray R, Winkler PW, Shaikh HS, Musahl V. HTO for varus deformity. *J Am Acad Orthop Surg.* 2021;5(7):e21.00141.
41. Kyung HS, Lee BJ, Kim JW, Yoon SD. Plate comparison in OWHTO. *Clin Orthop Surg.* 2015;7(2):185-190.
42. Han SB, Bae JH, Lee SJ, et al. Locking plate biomechanics in OWHTO. *Knee Surg Relat Res.* 2014;26(3):155-161.
43. Yazdi HR, Torkaman A, Babaki AE, et al. Fixation effect on tibial slope. *J Orthop Surg Res.* 2023;18:780.
44. Brosset T, Pasquier G, Migaud H, Gougeon F. OWHTO long-term outcomes. *Orthop Traumatol Surg Res.* 2018;104(4):477-482.
45. Roman MD, Mohor CI, Melinte PR, et al. Meniscal tear management with ACLR. *Appl Sci.* 2022;12(12):6175.
46. Kim DK, Park G, Wang JH, et al. Preoperative quadriceps strength and ACLR outcomes. *Sci Rep.* 2022;12:5830.
47. Fernandes TL, Moreira HH, Andrade R, et al. Anatomic ACL reconstruction outcomes. *Orthop J Sports Med.* 2021;9(6):23259671211013327.
48. Fox MA, Engler ID, Zsidai BT, et al. Anatomic ACL reconstruction paradigm. *J ISAKOS.* 2023;8(1):15-22.
49. Xu H, Zhang C. Femoral tunnel positioning. *Arthroscopy.* 2010;26(12):1566-1572.
50. Garofalo R, Moretti B, Kombot C, et al. Femoral tunnel placement. *J Orthop Surg Res.* 2007;2:10.
51. Paschos NK, Howell SM. ACL reconstruction principles. *EFORT Open Rev.* 2016;1(11):398-408.
52. Costa GG, Perelli S, Grassi A, et al. Minimizing graft failure risk. *J Exp Orthop.* 2022;9(1):26.
53. Zaffagnini S, Lucidi GA, Macchiarola L, et al. Long-term ACL reconstruction outcomes. *J Exp Orthop.* 2023;10(1):36.
54. Azer A, Ge D, Chan FJ. Tibial tunnel positioning techniques. *Arthroscopy Techniques.* 2025;14(3):103261.
55. Avadhani A, Rao PS, Rao SK. Tibial tunnel placement outcomes. *Singapore Med J.* 2010;51:413-417.
56. Nishio Y, Kondo E, Onodera J, et al. Double-bundle ACL reconstruction. *Orthop J Sports Med.* 2018;6(5).
57. Stone AV, Marx S, Conley CW. Partial ACL tear management. *J Am Acad Orthop Surg.* 2021;29(2):60-70.
58. Widner M, Dunleavy M, Lynch S. Outcomes based on graft type. *Curr Rev Musculoskelet Med.* 2019;12(4):460-465.
59. Xie X, Liu X, Chen Z, et al. BPTB vs hamstring graft meta-analysis. *Knee.* 2015;22(2):100-110.
60. Freedman KB, D’Amato MJ, Nedeff DD, et al. ACL graft comparison meta-analysis. *Am J Sports Med.* 2003;31(1):2-11.
61. Ristanis S, Tsepis E, Giotis D, et al. Hamstring graft neuromuscular impact. *Am J Sports Med.* 2009;37(11):2179-2186.
62. Neddermann A, Willbold E, Witte F, et al. Tunnel widening after ACLR. *Am J Sports Med.* 2009;37(8):1609-1617.
63. Vijay C, Santosh MS, Avinash C, Adarsh T. Peroneus longus graft RCT. *Orthop J Sports Med.* 2022.
64. Rudy K, Mustamsir E, Phatama KY. Tendon tensile strength comparison. *Int J Surg Open.* 2017;9:41-44.
65. Wiradiputra A, Febyan, Aryana G. Peroneus longus graft case review. *Int J Surg Case Rep.* 2021;83:106028.
66. He J, Tang Q, Ernst S, et al. Peroneus vs hamstring graft outcomes. *Knee Surg Sports Traumatol Arthrosc.* 2021;29(9):2869-2879.