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Knee kinesiography for dynamic assessment of anterior cruciate ligament ruptures: Potential for a pediatric application

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ABSTRACT

Anterior cruciate ligament (ACL) ruptures are common, particularly among athletes, and lead to altered biomechanics that complicate rehabilitation and return to activities. These alterations must be assessed to tailor therapeutic strategies and reduce the risk of long-term complications. This literature review examines the clinical applications of knee kinesiography, focusing on its role in evaluating dynamic knee adaptations following ACL rupture. It highlights the method's advantages over traditional motion analysis techniques and explores its potential use in pediatric populations.

This literature review was conducted in February 2025 in PubMed, Google Scholar, and Web of Science without date restrictions. Inclusion criteria were peer-reviewed studies involving patients with ACL ruptures and assessing knee biomechanics using knee kinesiography. Studies using laboratory-based motion capture systems, other portable technologies, case reports, or lacking a clear description of gait assessment methods were excluded.

Five cohort studies were included: four in adults with ACL deficiency and one in pediatric patients. Knee kinesiography allows objective, dynamic, weight-bearing assessment of knee kinematics across all three anatomical planes. It detects gait alterations post-ACL rupture, such as increased stance-phase knee flexion and abnormal tibial rotation. It supports personalized rehabilitation based on objective data. However, pediatric applications remain limited, and the lack of normative data restricts interpretation in this population.

Knee kinesiography is a valuable, accessible tool for dynamic analysis following ACL rupture. Clinically, it can guide individualized treatment strategies. Further pediatric research is needed to establish normative values and adapt this approach to younger populations.

1. Introduction

ACL ruptures are among the most common knee injuries in athletes, especially in teenagers and young adults involved in high-intensity pivot sports.[1,2] These injuries account for up to 50 % of all knee ligament injuries, with an estimated annual incidence of 200,000 cases in the United States alone.[3] Their prevalence is increasing worldwide due to the growing popularity of competitive sports.[3] ACL injuries can significantly impact quality of life by limiting physical activity, delaying return to sport, and increasing the risk of early-onset osteoarthritis.[4] Although conservative treatment may be appropriate in some cases, ACL rupture typically requires surgical ligament reconstruction.[5]

Post-rupture ACL-deficient (ACLD) and post-ACL reconstruction (ACLR) rehabilitation relies on accurate analysis of biomechanical deficits to tailor effective therapeutic protocols. Precise quantification of kinematic parameters is essential to objectively assess gait pattern changes caused by ACL rupture and to evaluate their functional impact on the knee joint. However, conventional assessments, primarily based

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on clinical observation or two-dimensional (2D) motion analysis systems, lack the precision required for a comprehensive understanding of these biomechanical alterations.[6] These traditional tools often fail to capture the complexity of three-dimensional (3D) knee movement, particularly in the transverse plane where parameters like tibial internal/external rotation play a critical role in joint stability.[7] While 2D systems can detect gross asymmetries, they cannot accurately quantify subtle movements such as dynamic valgus or tibial translation. Additionally, motion artifacts due to skin marker slippage or misalignment can compromise data accuracy.[8] Most of these methods also require controlled laboratory environments, costly infrastructure, and a time-consuming setup, thereby limiting their feasibility in routine clinical practice.[9] These constraints limit their routine use.

Knee kinesiography has been extensively studied in the context of knee osteoarthritis, where it has proven effective in identifying biomechanical abnormalities such as varus thrust, a subtle misalignment that is often difficult to detect visually but strongly associated with accelerated disease progression.[10,11] The clinical adoption of knee kinesiography represents a significant advancement in the evaluation of biomechanical alterations related to ACL rupture. It enables detailed, 3D numerical analysis that is essential to accurately monitor these changes, guiding rehabilitation, and ensuring a safe return to sport.

The objective of this literature review was to examine the clinical applications of knee kinesiography in ACL ruptures, highlight its advantages over traditional motion analysis techniques, and explore its role in orthopedic rehabilitation. It also aimed to evaluate its potential relevance in pediatric care.

2. Methods

This literature review was conducted in February 2025 using PubMed, Google Scholar, and Web of Science, with no date restrictions. Studies were included if they were peer-reviewed, published in English, involved patients with ACL ruptures (ACLD or ACLR), and assessed gait-related knee biomechanics using knee kinesiography (KneeKG™). Reviews were included if they reported relevant biomechanical data. Exclusion criteria were studies using only laboratory-based motion capture systems, portable technologies other than knee kinesiography (such as inertial sensors or camera-based systems), case reports, abstracts without full-text access, and articles lacking a clear description of the gait assessment methodology.

2.1. Technical description of knee kinesiography

Lustig et al. published a review identifying the KneeKG™ system as the most widely used and best-studied knee kinesiography model, while various studies report on its reliability and reproducibility.[4,12–14] This biomechanical tool was designed to analyze the 3D kinematics of the knee under functional conditions. The system combines passive motion sensors attached to a specialized harness, an infrared optical tracking system (Polaris Spectra, Northern Digital Inc.), and the Knee3D™ software (Fig. 1).[4]

This setup enables precise measurements of knee flexion/extension, adduction/abduction, internal/external tibial rotation, and anteroposterior tibial translation.[12] To ensure optimal accuracy, the KneeKG™ harness is mounted in a quasi-static manner on the thigh and calf, thereby minimizing artifacts caused by skin movement. This approach, combined with an advanced calibration methodology, ensures high measurement reliability, with intraclass correlation coefficients (ICCs) of 0.94 for flexion/extension, 0.92 for adduction/abduction, and 0.89 for internal/external rotation.[4] Standard measurement errors (SEM) remain low: 0.5° for flexion/extension, 0.4° for adduction/abduction, and 0.7° for internal/external rotation, increasing data reproducibility.[13,14]

The calibration process includes two main steps: identifying joint centers and defining joint axes. The KneeKG™ then records kinematic parameters during functional activities such as walking or squatting, enabling a precise evaluation of biomechanical impairments to track the rehabilitation progress. Each task highlights specific biomechanical knee impairments, allowing therapeutic protocols to be tailored according to each patient's needs and goals. For gait analysis, the data collected through knee kinesiography is normalized and averaged through a gait cycle from 0 to 100 %. The Knee3D™ software analyzes the captured data and generates detailed reports that allow clinicians to visualize and quantify biomechanical impairments.[15] These reports provide visual feedback not only for clinicians but also for patients, helping them better understand their biomechanical impairments and encouraging greater adherence to rehabilitation protocols.

3. Results

A total of 69 studies were identified and 62 were excluded because they did not meet the inclusion criteria. Among the 7 remaining studies that used knee kinesiography, two were excluded because they were single-patient case reports. Ultimately, five studies were included in this

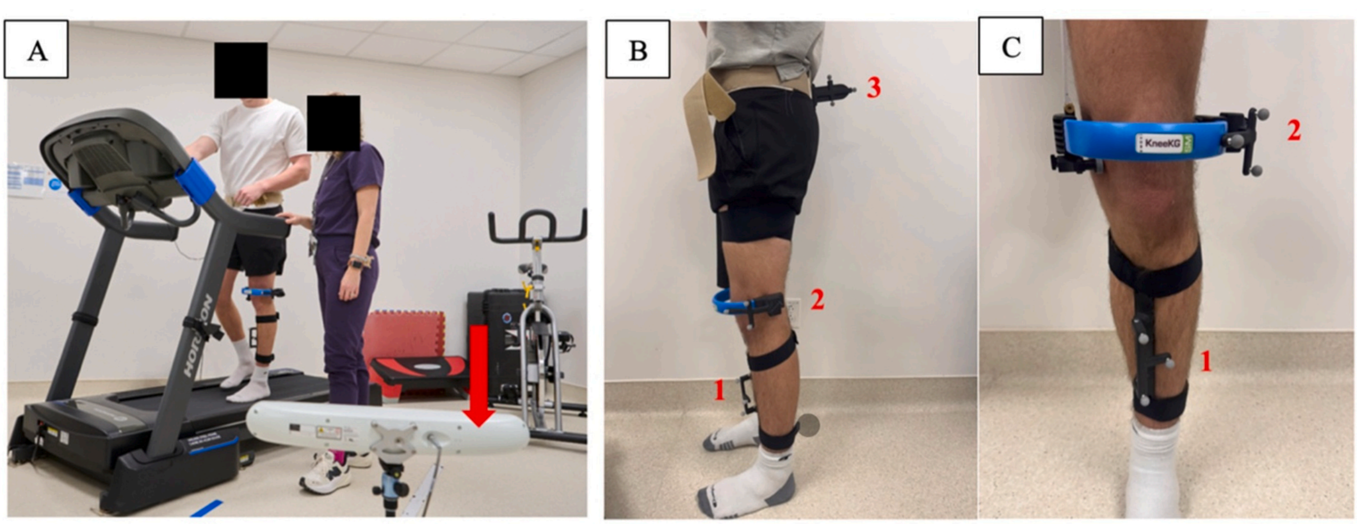

Fig. 1. A. KneeKG™ system with motion sensors for gait analysis on the left leg of a non-pathological subject. The red arrow indicates the infrared tracking system. **B.** Lateral view of the full KneeKG™ harness, including tibial (1), femoral (2), and sacral (3) markers. **C.** Frontal view of tibial (1) and femoral (2) markers placement.

review (Table 1). Of these studies, four analyzed knee joint biomechanics in adult ACLD populations and only one in an adolescent population (Fig. 2).

3.1. Clinical findings of knee kinesiography in ACL injuries

3.1.1. Sagittal plane: flexion/extension

Shabani et al. reported a significant reduction in knee extension during stance phase in ACLD patients (13.2° ± 2.1° vs. 7.3° ± 2.7° in controls).[16] This flexed-knee strategy limits anterior tibial translation but restricts functional range of motion. Although ACL reconstruction improves certain parameters, abnormal gait patterns often persist. Ayoubian et al. noted reduced peak flexion during swing phase[17] and Shabani et al. also demonstrated a significant reduction in knee extension of ACLR knees compared to healthy controls during terminal stance to initial swing,[9] indicating that short-term kinematic adaptations remain 6–12 months post-reconstruction. Though adaptive short-term, these changes may alter load distribution and accelerate joint degeneration.[18,19]

3.1.2. Axial plane: internal/external tibial rotation

Knee kinematic findings in the axial plane after ACL rupture are inconsistent, with no clear consensus. Several studies report increased internal tibial rotation during mid-stance. Shabani et al. found a mean difference of −1.4° ± 0.2° in ACLD knees vs. 0.2° ± 0.3° in controls.[9]

Table 1
Summary of studies published before February 2025 using knee kinesiography (KneeKG™ system) for kinematic analysis of the knee following an anterior cruciate ligament rupture. ACL; anterior cruciate ligament. ACLD; anterior cruciate ligament deficiency.

Authors (year)	Number of patients	Study Type	Measured outcomes	Key Finding/Key Results
Ayoubian et al. (2016)[2]	28	Pre- and post-reconstruction analysis of the ACL (adolescents)	3D kinematic variability (functional principal component analysis)	Significant reduction in kinematic variability after reconstruction, improved stability when walking.
Shabani et al. (2015)[3]	45	Kinematic analysis of ACLD patients (adults)	3D kinematics (tibial rotation, flexion-extension, abduction/adduction)	Significant alterations with increased flexion and excessive internal rotation during walking.
Shabani et al. (2015)[4]	45	Pre- and post-reconstruction analysis of the ACL (adults)	3D kinematics (tibial rotation, flexion-extension, abduction/adduction)	After ACL reconstruction, patients have better kinematic parameters, but they still differ from control patients.
Sideris et al. (2018)[5]	44	Comparison of 2 ACL reconstruction techniques	Rotational kinematics of the knee in 3D	Best rotary kinematics with 5-strand hamstring autograft, improving dynamic stability.
Fuentes et al. (2010)[6]	20	Observational Study of Chronic ACLD Patients (Adults)	3D kinematics of the knee when walking (axial rotation analysis)	Demonstration of an adaptive gait pattern: cheerful pivot-shift avoidance, with increased external tibial rotation to avoid subluxation.

Although statistically significant, this 1.2° difference is often considered clinically negligible, within the measurement error range, and not typically actionable in clinical practice. Lustig et al. observed persistent internal tibial rotation during push-off in most ACLR patients.[4] While reconstruction improves rotational control, internal rotation often remains higher compared to healthy subjects. In fact, Shabani et al. saw no difference between ACLD and ACLR patients during the entire gait cycle.[9] This residual rotation may overload the medial compartment which can play a role in accelerated cartilage degeneration.[19]

On the contrary, other studies challenge these patterns. Fuentes et al. described a "pivot-shift avoidance gait," where ACLD patients show increased external tibial rotation during pre-swing instead, likely to avoid unstable internal rotation and anterior subluxation.[20] This suggests that biomechanical responses could vary based on injury stage, individual neuromuscular strategies, and compensation mechanisms.

3.1.3. Coronal plane (abduction/adduction) and anterior-posterior translation

Although anterior tibial translation and adduction are more apparent in static tests (e.g., Lachman or anterior drawer), Shabani et al. found no significant difference during weight-bearing gait between ACLD patients and controls.[9] They also reported no significant differences between ACLR knees and healthy controls, suggesting that certain dynamic alterations may remain subtle or undetectable during gait analysis.[16] These displacements may be masked by compensatory hamstring contraction, which stabilizes the joint.[21,22]

3.1.4. Kinematic variability and functional stability assessment

While most studies focus on discrete angular parameters (e.g., peak flexion or tibial rotation), Ayoubian et al. proposed using Functional Principal Component Analysis (FPCA) to assess knee kinematic variability in three planes using the KneeKG™ system.[17] Their study on adolescents reported a significant reduction in 3D gait variability six months post-ACL reconstruction, especially in flexion/extension and internal/external rotation angles.[17] Notably, 82 % of patients showed significantly reduced sagittal plane variability, supporting that variability metrics can reflect improved dynamic stability and neuromuscular control post-surgery.[17] This highlights the clinical potential of integrating variability-based analyses alongside classical angle-based measures in pediatric ACL research.

3.2. Pediatric applicability

Rehabilitation of young ACL patients poses unique challenges due to ongoing growth and neuromuscular development.[24] Clinical approaches must be adjusted to avoid growth plate damage while restoring joint stability and neuromuscular function.[25] Higher graft failure rates in this group further justify tailored, cautious rehabilitation protocols.[26]

Open growth plates in children and adolescents complicate ACL rehab. Ongoing bone growth can lead to postural and biomechanical changes, such as dynamic valgus or varus.[27] These kinematic variations require age- and maturity-specific rehabilitation strategies.[28] Current protocols rely largely on adult data, limiting their relevance for pediatric patients.[26] There is a pressing need for pediatric-specific databases to guide treatment based on age, growth stage, and activity level. Integrating knee kinesiography could provide precise 3D data and help optimize individualized rehabilitation, potentially reducing graft failure in this high-risk group.[29]

4. Discussion

4.1. Advantages and limitations of knee kinesiography

4.1.1. Comparison with traditional methods

Clinicians typically assess knee dynamics using physical tests (Lachman, anterior/posterior drawer, pivot-shift) and gait

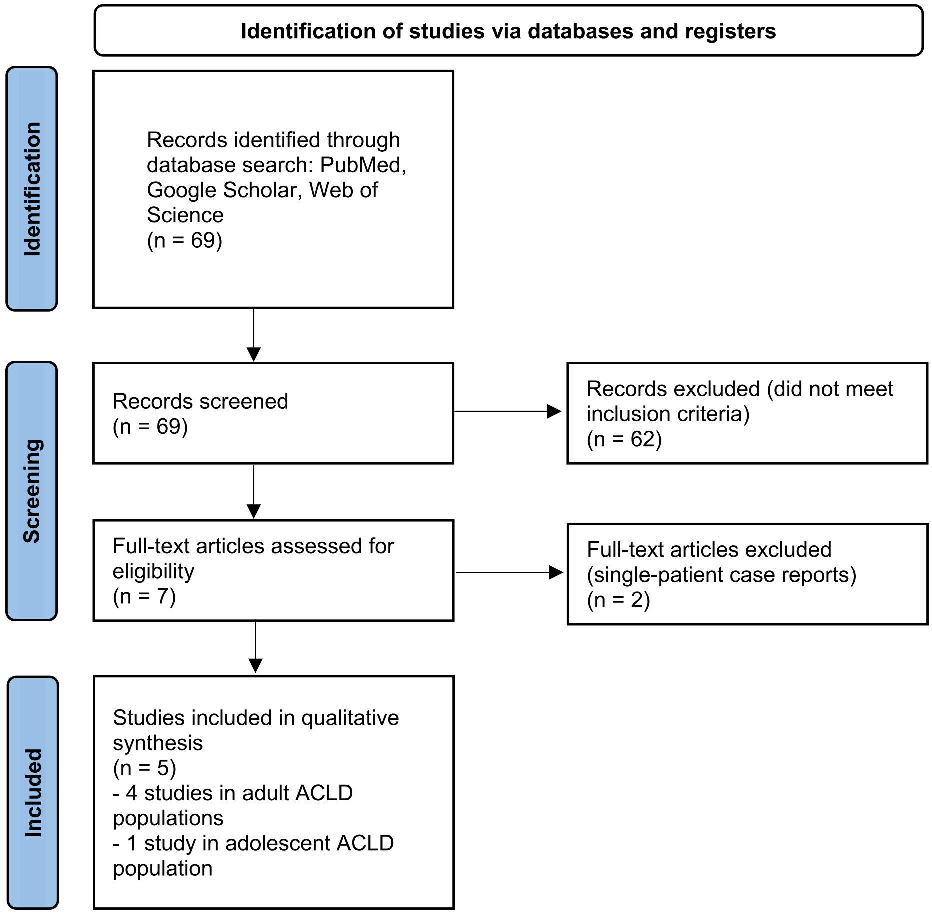

Fig. 2. Flow diagram illustrating the study identification, screening, and inclusion process.

Source: Page MJ et al. BMJ 2021; 372:n71. doi: 10.1136/bmj.n71.

observation.[30] While useful to detect obvious laxity, these rely on palpation, leading to inter-examiner variability and lacking precise 3D quantification.[31] In rare cases, 2D video or clinical gait labs are used for motion analysis.[32,33] These methods offer basic assessments but are limited—subjective and imprecise when detecting subtle changes, especially in the frontal (varus/valgus) and transverse (rotation) planes, where motion is minimal and can be masked by nearby joints.[33] Radiological approaches (e.g., coronal alignment, posterior tibial slope) provide quantifiable 2D data but do not capture the dynamic, 3D nature of movement.[34,35] Importantly, knee kinesiography is not intended to replace established clinical assessments or imaging tools such as MRI, which remain essential for diagnosing structural lesions and guiding surgical decisions.[36] Rather, it should be viewed as a complementary tool that provides additional insight into dynamic instability and functional impairments during movement. By integrating both structural and functional data, clinicians can achieve a more comprehensive understanding of the patient's condition and tailor management strategies accordingly.

4.1.2. Benefits

Derived from advanced biomechanical research, knee kinesiography enables a real-time, extremely precise, non-invasive 3D assessment of knee kinematics. Unlike traditional systems, often complex, expensive, and impractical for routine use, it is portable, user-friendly, and allows dynamic, weight-bearing measurements for realistic functional analysis.[4] A key strength is its ability to generate a patient-specific kinematic "signature," capturing detailed motion in all three planes (flexion/extension, abduction/adduction, tibial rotation) while accounting for individual anatomical and biomechanical variations.[4]

Knee kinesiography effectively detects biomechanical impairments linked to ACL ruptures, including increased internal tibial rotation and altered knee flexion during gait.[23] By providing a precise baseline for pre- and post-intervention tracking, it supports customized treatment to prevent recurrence.[12] Its ability to quickly generate clear visual outputs also enhances patient understanding and communication, promoting better therapy adherence.[4,9]

4.1.3. Limitations

This review has several limitations. First, only five studies met the inclusion criteria, which limits the breadth and generalizability of the findings. The small number of included articles reflects the novelty of this research area and underscores the need for further studies, particularly in pediatric populations. Second, while all included studies used knee kinesiography, their designs, populations, and reported outcomes varied, which may affect the comparability of results. Finally, this review focused exclusively on studies using a single motion analysis system (KneeKG™), which may have introduced a selection bias and limited the generalizability of the findings to other motion analysis tools, namely inertial sensor-based or laboratory-based systems. Future research comparing different knee motion analysis methods would help to validate and contextualize these findings across technologies.

4.2. Future directions

Studies on knee kinesiography in pediatrics remain scarce, particularly for post-ACL rupture or reconstruction assessments. Few have examined how knee biomechanics evolve with growth in this population.[4,25] Longitudinal studies are needed to assess how growth and rehabilitation protocols impact kinematic outcomes over time. These could clarify how residual deficits affect long-term joint function and help refine treatment strategies. Knee kinesiography may also detect graft-specific differences in biomechanical recovery after ACL reconstruction, supporting more personalized rehabilitation based on patient profiles and surgical techniques. This tool could help identify early predictors of reinjury and guide individualized rehabilitation to improve long-term outcomes.[26] Assessing its clinical feasibility in children is essential to validate its role in pediatric evaluation and prevention.[24] Lastly, integrating kinesiography with artificial intelligence could enable real-time, predictive recommendations tailored to each patient. There is also a critical need to develop normative databases for children and adolescents, enabling more accurate, age-specific treatment approaches and ultimately improving care for this vulnerable population.

4.3. Potential applications of knee kinesiography in other sports medicine conditions

Although designed for knee kinematic analysis, knee kinesiography may indirectly assess other joints involved in gait through a patient's biomechanical signature. Gait deviations caused by ankle, hip, or spinal issues can manifest at the knee. For example, a patient with femoroacetabular impingement may adopt external leg rotation, detectable at the knee level via kinesiography.[37]

The 3D dynamic motion analysis used in kinesiography can help identify compensatory patterns in broader musculoskeletal disorders. This approach has been used to analyze human locomotion and posture-related issues in asymmetrical sports like tennis or golf.[38] Postural assessments have shown clinical value in primary care to identify musculoskeletal disorders.[39]

Integrating kinesiography into the evaluation of such conditions could support more personalized rehabilitation strategies, reducing the risk of secondary injuries. A detailed biomechanical signature could indicate issues such as "probable ACL rupture," "right-sided hip impingement," "left ankle laxity," or "flat feet," based solely on gait curves. This would alert clinicians to possible comorbidities without the need for additional sensors. Prior studies have already shown that motion analysis and biomechanical modeling are valuable when investigating locomotor pathologies, reinforcing the role of such technologies in modern rehabilitation approaches.[38]

5. Conclusion

ACL ruptures significantly alter knee biomechanics. Knee kinesiography, via the KneeKG™ system, offers dynamic, 3D, weight-bearing analysis for precise quantification of these changes. This review highlights its value in identifying ACL rupture deficits and guiding rehabilitation based on objective parameters. However, the lack of normative pediatric data limits its current use in this population. Further studies are needed to validate its application in children and improve early ACL rupture management.

Informed consent

Not applicable.

Author contributions

Conceptualization by MLN, NH, and DM; Data curation by AM, AB, SM, and DM; Formal analysis by DM, SM, AB, AM, MLN; Methodology MLN, NH, DM; Project administration by MLN; Software by AM, AB, SM; Supervision by MLN; Roles/Writing – original draft by AM; Writing – review & editing by all authors.

Ethical statement

Not applicable.

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Declaration of competing interest

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