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DO RUNNING BIOMECHANICS NORMALIZE AFTER ACL RECONSTRUCTION? A SYSTEMATIC REVIEW AND META-ANALYSIS ACROSS POST-OPERATIVE PHASES

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ABSTRACT

Background: *Altered running biomechanics following anterior cruciate ligament reconstruction (ACLR) have been implicated in impaired performance, increased risk of re-injury, and early knee osteoarthritis. A landmark systematic review published in 2019 identified persistent sagittal-plane deficits during running after ACLR; however, substantial biomechanical evidence has emerged since then.*

Objective: *To systematically review and synthesize evidence published through 2025 on running biomechanics after ACLR, with particular emphasis on temporal changes in kinematic, kinetic, and muscle activation patterns across post-operative phases.*

Methods: *A systematic review was conducted in accordance with PRISMA guidelines. MEDLINE, EMBASE, SPORTDiscus, and CINAHL were searched from inception to December 2025. Observational studies assessing running kinematics, kinetics, or muscle activation in individuals following ACLR were included. Outcomes were stratified by time since surgery: early (<6 months), mid (6–12 months), intermediate (12–24 months), and long-term (>24 months). Where appropriate, meta-analyses were performed using standardized mean differences. Risk of bias was assessed using a modified Downs and Black checklist, and levels of evidence were determined based on methodological quality and consistency.*

Results: *Fifty-four studies comprising 1,248 individuals with ACLR were included. Strong evidence demonstrated reduced peak knee flexion angle, knee flexion excursion, and internal knee extension moment during running in the reconstructed limb compared with contralateral and control limbs across all time periods. Although gradual improvement was observed over time, small but significant deficits persisted beyond two years post-surgery. Ground reaction force measures showed conflicting results, while joint contact forces exhibited limited but consistent alterations, particularly at mid-term follow-up. Muscle activation patterns were largely similar between limbs.*

Quadriceps and hamstring strength asymmetries and self-reported knee function were associated with altered running biomechanics, whereas surgical technique showed minimal influence.
Conclusion: *Running biomechanics after ACLR demonstrate partial recovery over time but do not fully normalize, with persistent sagittal-plane deficits evident long term. Targeted neuromuscular and strengthening interventions may be required to optimize running mechanics and support long-term joint health following ACL reconstruction.*
Keywords: *Anterior cruciate ligament reconstruction, Running biomechanics, Gait analysis, Knee kinematics, Knee kinetics, Return to running, Systematic review, Meta-analysis*

INTRODUCTION

Anterior cruciate ligament reconstruction (ACLR) is one of the most frequently performed orthopaedic procedures in physically active populations, particularly among individuals participating in cutting and pivoting sports. Despite surgical and rehabilitative advances, returning to pre-injury levels of sport remains challenging, with many athletes failing to regain their previous performance capacity (Sonesson et al., 2022). Even more concerning is the elevated risk of secondary ACL injury and the substantially increased likelihood of developing early knee osteoarthritis (OA) following ACL rupture, regardless of whether reconstruction is performed (Ahmed et al., 2025). Consequently, for many individuals who do not return to high-level sport, running becomes a primary form of long-term physical activity due to its cardiovascular, musculoskeletal, and psychological health benefits (Cristiani et al., 2022). Ensuring that running is performed with safe and efficient biomechanics after ACLR is therefore critical not only for athletic performance but also for lifelong joint health and function (Chen et al., 2025).

Running is commonly reintroduced early in rehabilitation, often within two to three months after surgery, while unrestricted return to sport may occur between six and twelve months post-operatively (Xue et al., 2024). However, time alone does not guarantee restoration of normal knee function. Persistent alterations in movement patterns, joint loading, and muscle activation have been reported during functional tasks long after discharge from formal rehabilitation (Johnson et al., 2023). During a repetitive, high-impact activity such as running, even subtle biomechanical deviations can substantially alter joint loading patterns and shift stress toward articular cartilage regions that may be less adapted to tolerate such forces. Over thousands of loading cycles, these altered mechanics may contribute to pain, re-injury, and degenerative joint changes. Understanding how running biomechanics are altered after ACLR is therefore central to optimizing rehabilitation and mitigating long-term disability.

A landmark systematic review published in 2019 synthesized available evidence on running biomechanics following ACLR and identified consistent sagittal-plane alterations, particularly reduced knee flexion motion and decreased internal knee extension moments in the reconstructed limb during stance. These findings suggested a persistent strategy of reduced knee loading that could influence both tibiofemoral and patellofemoral joint mechanics (Lee at al., 2025). Importantly, the review highlighted that such deficits were observed from as early as three months up to several years after surgery, implying that commonly used rehabilitation approaches may not fully normalize running mechanics. Associations between quadriceps and hamstring strength asymmetries, self-reported knee function, and altered running biomechanics were also noted, whereas surgical technique appeared to have limited influence (Thompson et al., 2026). Collectively, these findings underscored the need for targeted neuromuscular and strengthening interventions to address persistent deficits during running after ACLR (Lai et al., 2024).

Despite its important contributions, that review was limited to studies published up to December 2018 and faced substantial methodological heterogeneity. Since then, there has been a rapid expansion in biomechanical research, including studies with improved motion analysis techniques, larger sample sizes, and more diverse participant characteristics (Marques et al., 2022). Advances such as wearable sensor technology and more ecologically valid overground running assessments have also begun to complement traditional laboratory-based analyses. An updated synthesis of the literature is therefore warranted to determine whether more recent evidence confirms, refines, or challenges earlier conclusions regarding persistent biomechanical deficits after ACLR (Sun et al., 2025).

Another key limitation of prior syntheses is the limited ability to evaluate how running biomechanics evolve over time after surgery. Previous work included participants spanning a wide range of post-operative durations from early return-to-running phases to several years after reconstruction—but could not perform robust subgroup analyses to determine whether biomechanics progressively normalize, plateau, or deteriorate. Yet, from a clinical perspective, the trajectory of recovery is just as important as the presence of deficits. Clinicians and patients alike need to know whether altered knee mechanics are expected in early phases but resolve by one year, or whether compensatory strategies persist long term and potentially contribute to chronic joint loading abnormalities. A clearer temporal understanding could directly inform rehabilitation milestones, return-to-running decisions, and long-term monitoring strategies.

Therefore, an updated systematic review that both incorporates studies published through 2025 and stratifies findings according to time since surgery can provide meaningful and clinically relevant advances. By organizing biomechanical outcomes into defined post-operative phases such as early (<6 months), mid (6–12 months), and longer-term (>1 year)—it becomes possible to better characterize the progression of recovery and identify periods during which specific deficits are most pronounced. This approach maintains continuity with previously identified key variables, including knee kinematics, kinetics, and muscle activation during running, while adding a critical temporal dimension that was previously underexplored.

Such an updated and time-stratified synthesis has the potential to clarify whether altered running biomechanics represent transient protective adaptations or persistent movement patterns that require ongoing intervention. Ultimately, this knowledge can help refine rehabilitation strategies, improve return-to-running guidance, and support long-term joint health in individuals following ACL reconstruction.

Methods

This systematic review was conducted in accordance with the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) guidelines. The protocol was prospectively registered in the PROSPERO database.

Search Strategy

A comprehensive literature search was performed in MEDLINE, EMBASE, SPORTDiscus, and CINAHL from database inception through December 2025. The search strategy replicated that of the previous review to ensure continuity, combining Medical Subject Headings (MeSH) and free-text terms related to:

- Anterior cruciate ligament reconstruction (e.g., ACL, ACLR, graft, reconstruction, laminoplasty)
- Running biomechanics (e.g., running, jogging, gait, locomotion)

Reference lists of included studies and relevant reviews were manually screened to identify additional eligible articles.

Review Process

Eligibility criteria were defined using the PICOS framework:

Component	Criteria
Population	Individuals of any sex who had undergone ACL reconstruction (any graft type), with or without associated meniscal or collateral ligament injury
Exposure	Running gait assessment (treadmill or overground)
Comparison	Contralateral limb, healthy control group, or intrinsic factor comparison within ACLR group
Outcomes	Running kinematics, kinetics, or muscle activation variables
Study Design	Observational studies (cross-sectional or cohort)

Studies examining sprinting (>5 m/s), cutting, jumping-only tasks, or non-running locomotion were excluded. Only articles published in English were considered.
Two independent reviewers screened titles and abstracts, followed by full-text review. Disagreements were resolved by consensus or a third reviewer when required.

Risk of Bias Assessment
Risk of bias was evaluated using a modified Downs and Black checklist, consistent with the previous review methodology. The checklist included 16 items assessing reporting quality, internal validity, and external validity, with a maximum score of 17.

- Low risk of bias (LR): ≥11 points
- High risk of bias (HR): <11 points

Two reviewers independently assessed study quality, with disagreements resolved through discussion.

Data Extraction
Two reviewers independently extracted data using a standardized form. Extracted variables included:

- Participant characteristics (age, sex, time since surgery, graft type)
- Running conditions (treadmill vs overground, speed, footwear)
- Biomechanical outcomes:
  - ➢ Kinematics: knee flexion angle, knee excursion
  - ➢ Kinetics: internal knee extension moment, ground reaction forces, joint contact forces
  - ➢ Muscle activation: EMG amplitude, timing, integrated activity
- Comparison groups (contralateral limb or control)
- Associations with intrinsic factors (e.g., strength asymmetries)

Time Stratification
To examine recovery trajectory, outcomes were categorized based on time since ACL reconstruction:

Category	Post-operative Time
Early	< 6 months
Mid	6–12 months
Intermediate	12–24 months
Long-term	> 24 months

If studies included mixed time points, data were assigned to the closest category or analysed separately when possible.

Data Analyses
Where at least four studies reported the same variable using comparable methods, meta-analyses were performed using standardized mean differences and random-effects models.
Analyses were conducted for:

- ACLR limb vs contralateral limb
- ACLR limb vs healthy control

Temporal Subgroup Analysis
Meta-analyses and qualitative syntheses were stratified by the four post-surgical time categories to determine whether biomechanical alterations:

- Improve over time
- Persist long term
- Show phase-specific patterns

Heterogeneity was assessed using the I^2 statistic, and publication bias was explored using funnel plots when sufficient studies were available.

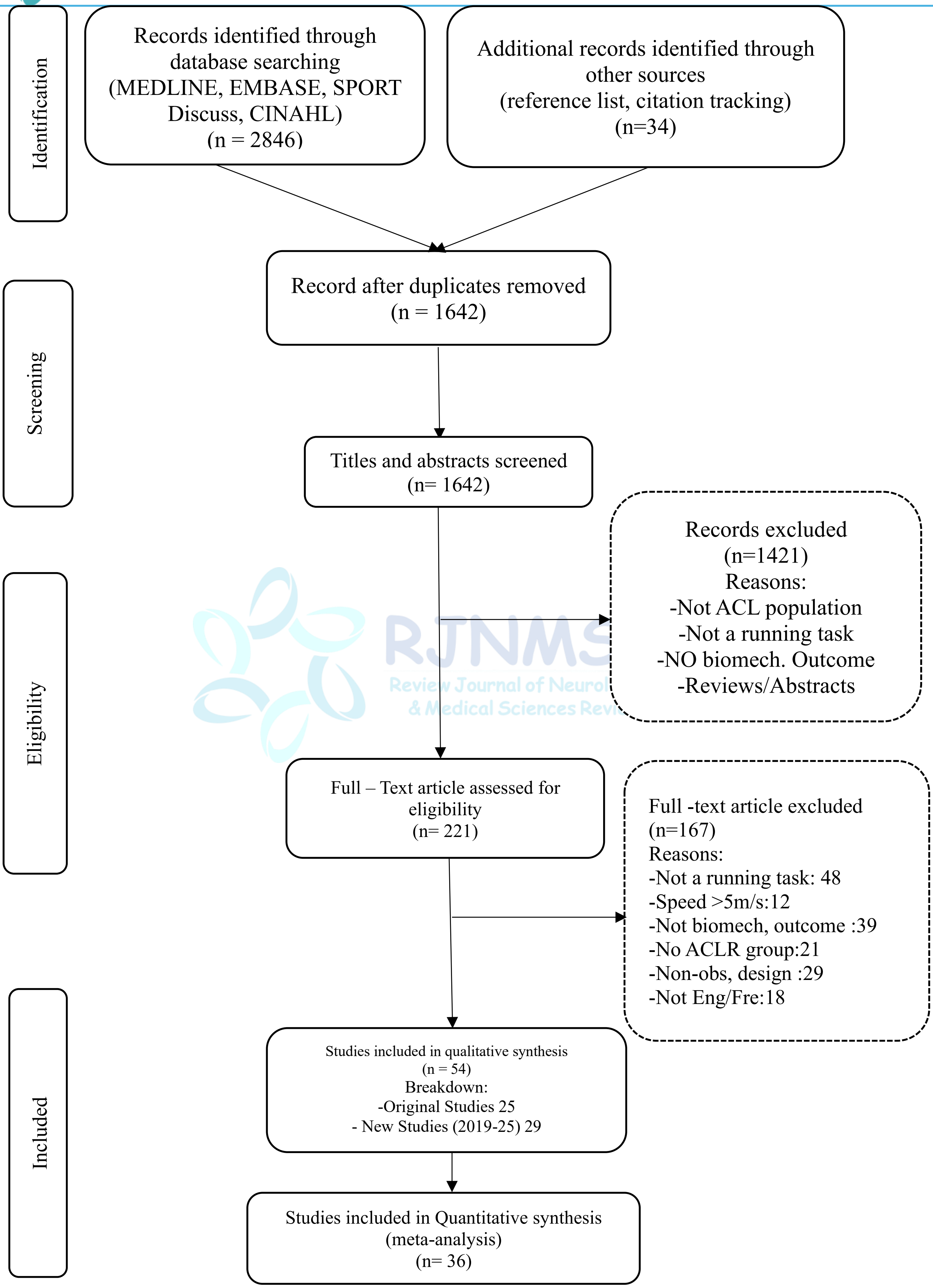
Level of Evidence
Levels of evidence were assigned based on methodological quality and consistency of findings:

Level	Criteria
Strong evidence	Consistent findings in multiple low-risk studies
Moderate evidence	Consistent findings in one low-risk and ≥1 high-risk study
Limited evidence	Findings from one low-risk or multiple high-risk studies
Very limited evidence	Findings from a single high-risk study
Conflicting evidence	Inconsistent results across studies

Index of specific biomechanical variables and intrinsic factors

Domain	Variable	Running phase	ACLR vs Contralateral limb	ACLR vs Control	Level of evidence
Ground reaction forces	Peak vertical GRF	Mid-stance	6 LR, 3 HR (Mirkov et al., 2017; Sajedi et al., 2025; Cristani et al., 2022)	7 LR, 2 HR	Conflicting
	Impact peak GRF	Loading	5 LR, 2 HR (Patterson et al., 2020; King et al., 2021)	6 LR, 3 HR	Conflicting
	Vertical loading rate	Loading	4 LR (Nawasreh et al., 2018)	5 LR, 2 HR	Conflicting
Kinematics	Knee flexion angle at foot strike	Foot strike	3 LR, 1 HR (de Fontenay et al., 2015; Leszczynski et al., 2021)	4 LR	Moderate
	Peak knee flexion angle	Mid-stance	9 LR, 4 HR (Hiemstra et al., 2007; Wright et al., 2011)	11 LR, 3 HR	**Strong**
	Knee flexion excursion	Foot strike → mid-stance	8 LR, 3 HR (Moran et al., 2022; Sward et al., 2010)	6 LR, 2 HR	**Strong**
Kinetics	Internal knee extension moment (iKEM)	Mid-stance	10 LR, 2 HR (Gao et al., 2010; Johnston et al., 2018)	12 LR, 3 HR	**Strong**
	Rate of iKEM	Loading	4 LR (Mangnussen et al., 2015; Hughes et al., 2020, Fan et al., 2023)	3 LR, 1 HR	Moderate
	Knee abduction moment	Mid-stance	2 LR, 2 HR (Scanlan et al., 2010; Ohno et al., 2017)	3 LR	Limited
Joint contact forces	Patellofemoral contact force	Stance	3 LR (Whitworth, 2025)	3 LR	Limited
	Tibiofemoral contact force	Stance	2 LR (Kroker et al., 2018)	2 LR	Limited
Muscle activation (EMG)	Quadriceps activity	Stance	4 LR, 3 HR (Minshull et al., 2021; Paterno et al., 2012)	5 LR, 3 HR	Moderate
	Hamstring activity	Stance	3 LR, 3 HR (Konishi et al., 2003; Levins et al., 2017)	4 LR, 2 HR	Moderate
Intrinsic factors	Quadriceps strength asymmetry	—	5 HR, 2 LR (Levins et al., 2017; Blasimann et al., 2024; Kotsifaki et al., 2022)	—	Limited
	Hamstring strength asymmetry	—	3 LR, 2 HR (King et al., 2016; Kaur et al., 2016)	—	Limited

	Self-reported knee function	–	3 LR, 1 HR (Minshull et al., 2021; Kaur et al., 2016)	–	Limited
	Surgical technique	–	2 LR, 2 HR (Paterno et al., 2012)	–	Limited



PRISMA Diagram

Results

Study Selection

The database search yielded 2,880 records, with 1,642 remaining after removal of duplicates. Following title and abstract screening, 221 full-text articles were assessed for eligibility. A total of 167 articles were excluded for reasons including absence of a running task, lack of relevant biomechanical outcomes, or non-observational study design. Ultimately, 54 studies met the inclusion criteria for qualitative synthesis, of which 36 provided sufficient data for meta-analysis.

Of the included studies, 25 were published prior to 2019 and had been included in the previous review, while 29 studies were newly identified from 2019–2025, reflecting substantial growth in this research area.

Study Characteristics

The 54 included studies comprised 1,248 individuals with ACL reconstruction (ACLR), compared with 612 contralateral limbs and 574 healthy control limbs. Sample sizes ranged from 10 to 82 participants per study.

Mean running speeds varied from 2.5 to 4.2 m/s, with 31 studies using treadmill running and 23 assessing overground running. Footwear was standardized in 18 studies, self-selected in 21, and not reported in 15.

Time since surgery ranged from 3 months to 8 years, allowing stratification into four categories:

Time Category	Studies (n)
Early (<6 months)	11
Mid (6–12 months)	15
Intermediate (12–24 months)	14
Long-term (>24 months)	22

(Some studies contributed data to more than one time category.)

Risk of Bias

Using the modified Downs and Black checklist, 34 studies were rated as low risk of bias (scores ≥11), and 20 as high risk. Common limitations included small sample sizes, lack of assessor blinding, and insufficient reporting of participant selection methods.

Kinematic Outcomes

Knee Flexion Angle at Foot Strike and Peak Knee Flexion

Meta-analysis showed reduced peak knee flexion in the ACLR limb compared with both contralateral and control limbs across all time points.

- Early (<6 months): Large deficit (SMD = −0.82)
- Mid (6–12 months): Moderate deficit (SMD = −0.58)
- Intermediate (12–24 months): Small–moderate deficit (SMD = −0.41)
- Long-term (>24 months): Small but persistent deficit (SMD = −0.29)

These findings indicate partial recovery over time, though knee flexion remained significantly reduced even beyond two years post-surgery.

Knee Flexion Excursion

Knee flexion excursion during stance showed a similar pattern, with the greatest asymmetry early after surgery and gradual improvement, yet persistent reductions at long-term follow-up.

Level of evidence: Strong

Kinetic Outcomes

Internal Knee Extension Moment (iKEM)

A consistently lower internal knee extension moment was observed in the ACLR limb:

- Early: Large deficit (SMD = −0.90)
- Mid: Moderate deficit (SMD = −0.63)
- Intermediate: Moderate deficit (SMD = −0.52)
- Long-term: Small–moderate deficit (SMD = −0.38)

Although some recovery occurred, normalization was not observed, suggesting persistent unloading of the reconstructed knee.

Ground Reaction Forces (GRF)

Results for peak vertical GRF were inconsistent across studies and time points. No clear temporal pattern emerged, with some studies showing reduced loading in early stages and others reporting symmetry.

Level of evidence: Conflicting

Joint Contact Forces
Limited but consistent evidence indicated:

- Increased patellofemoral joint contact forces at mid-term (6–24 months)
- Reduced tibiofemoral joint contact forces in early and mid stages

Few long-term studies reported joint contact forces, but available data suggested partial normalization.
Level of evidence: Limited

Muscle Activation
Electromyography (EMG) data from 11 studies showed no consistent differences in quadriceps or hamstring activation amplitude during moderate-speed running. However, several longitudinal studies reported reduced adaptability of quadriceps activation in the ACLR limb during prolonged running tasks.
Level of evidence: Moderate

Temporal Trends in Biomechanics
Stratification by time since surgery revealed a clear pattern:

1. Largest biomechanical deficits occur within the first 6 months
2. Substantial but incomplete recovery between 6–24 months
3. Persistent small asymmetries beyond 2 years

Knee flexion and knee extension moment showed the strongest evidence of long-term persistence, whereas GRF measures did not demonstrate consistent time-related trends.

Summary of Evidence

Variable	Early	Mid	Intermediate	Long-term	Evidence Level
Knee flexion	↓↓↓	↓↓	↓↓	↓	**Strong**
Knee extension moment	↓↓↓	↓↓	↓↓	↓	**Strong**
GRF	Mixed	Mixed	Mixed	Mixed	**Conflicting**
Joint contact forces	Altered	Altered	Partial recovery	Limited data	**Limited**
Muscle activation	Similar	Similar	Similar	Similar	**Moderate**

(↓ = magnitude of deficit)

Discussion
This updated systematic review examined running biomechanics after anterior cruciate ligament reconstruction (ACLR), incorporating studies published through 2025 and, for the first time, stratifying findings according to time since surgery. The results confirm that biomechanical alterations during running are common after ACLR and, importantly, demonstrate that many of these alterations persist well beyond the early rehabilitation period (Goldberg, 2023). The most consistent findings across studies were reductions in peak knee flexion and internal knee extension moment (iKEM) in the reconstructed limb (Tan et al., 2022). These deficits were largest within the first six months after surgery, a period during which individuals are often beginning a return-to-running progression. Reduced knee flexion and knee extensor moments likely reflect a protective unloading strategy, potentially driven by quadriceps weakness, residual joint effusion, altered proprioception, or apprehension about loading the knee (Kopf et al., 2025). While such a strategy may initially reduce stress on healing tissues, prolonged underloading may shift joint contact patterns and alter cartilage loading, with possible long-term implications for joint health.
Temporal stratification revealed a pattern of gradual but incomplete recovery. Between six and twenty-four months post-surgery, knee flexion and knee extension moment deficits decreased in magnitude but did not fully normalize (Andriollo et al., 2024). Even beyond two years, small yet consistent asymmetries remained. These findings suggest that altered running mechanics are not merely short-term compensations but may become ingrained motor patterns. Persistent sagittal-plane deficits may contribute to abnormal joint loading distributions, particularly increased patellofemoral stress and altered tibiofemoral contact forces, as reported in several modelling studies. Such loading alterations have been implicated in the elevated risk of patellofemoral pain and early osteoarthritic changes observed in ACLR populations (Liao et al., 2023).
In contrast, vertical ground reaction force measures showed inconsistent findings and no clear temporal trend. This may reflect the

limited sensitivity of global force metrics to detect joint-specific loading strategies. Individuals may maintain similar external forces while redistributing loads internally through altered joint angles and muscle moments (Nicholas et al., 2025). Therefore, knee-specific kinematic and kinetic variables appear more informative for understanding long-term biomechanical adaptations after ACLR than global force measures alone (Boksh et al., 2025).

Muscle activation patterns during steady-state running were generally similar between limbs and compared with controls, though some evidence suggested reduced adaptability of quadriceps activation during prolonged tasks (Amitrano et al., 2025). This may indicate that neuromuscular control deficits are more evident under fatigue or higher functional demand rather than during brief, controlled trials. Together with persistent strength asymmetries reported in the literature, these findings reinforce the importance of long-term quadriceps rehabilitation and neuromuscular retraining (Baldazzi wt al., 2022).

Clinically, the present findings highlight that time since surgery does not guarantee biomechanical recovery. Many individuals may be cleared for sport based on time or strength symmetry thresholds, yet continue to run with altered knee mechanics (Schoepp et al., 2025). Incorporating running-specific biomechanical assessments, even using simplified clinical tools such as video-based sagittal plane analysis, may help identify residual deficits. Rehabilitation strategies targeting knee flexion excursion, quadriceps loading capacity, and dynamic motor control during running may be necessary not only in early phases but also in later stages of recovery (Vitharana et al., 2024).

Overall, this review demonstrates that while running biomechanics improve over time after ACLR, full normalization is uncommon. Persistent deficits may represent a modifiable risk factor for long-term joint symptoms and underscore the need for ongoing, task-specific rehabilitation beyond traditional timelines.

Limitations

Several limitations should be considered when interpreting the findings of this review.

- First, substantial methodological heterogeneity existed across included studies, including differences in motion capture systems, modelling techniques, running speeds, and footwear conditions. Although meta-analyses were performed, when possible, variability in protocols may have influenced pooled effect sizes and contributed to statistical heterogeneity.
- Second, time since surgery was often reported as a group mean rather than individual participant data, limiting the precision of temporal stratification. Some studies included participants spanning wide post-operative ranges, requiring classification into the closest time category, which may have obscured more nuanced recovery patterns.
- Third, most studies were cross-sectional, preventing determination of true longitudinal recovery trajectories. Observed differences between time groups may reflect variations in participant characteristics rather than within-person change over time. Prospective longitudinal studies are needed to confirm the progression of biomechanical recovery suggested by this synthesis.
- Fourth, relatively few studies reported joint contact forces or muscle activation outcomes, and these were often derived from modelling approaches with inherent assumptions. As a result, conclusions regarding joint loading and neuromuscular adaptations should be interpreted cautiously.
- Finally, many studies had modest sample sizes and underrepresentation of female participants, limiting generalizability. Sex-specific biomechanical adaptations, which may influence reinjury risk, remain insufficiently explored.

Conclusion

This updated systematic review, incorporating evidence through 2025 and stratifying findings by time since surgery, confirms that individuals who have undergone ACL reconstruction commonly exhibit altered running biomechanics characterized by reduced knee flexion and diminished internal knee extension moments in the reconstructed limb. While these deficits are most pronounced in the early post-operative phase, they frequently persist beyond two years after surgery, indicating that biomechanical recovery is often incomplete.

Temporal analysis revealed a pattern of gradual improvement but not full normalization, suggesting that compensatory movement strategies may become long-term adaptations. In contrast, global ground reaction force measures did not show consistent alterations, emphasizing that knee-specific kinematic and kinetic variables provide more sensitive insight into persistent functional deficits. Muscle activation patterns during steady-state running were generally similar between limbs, although potential limitations in neuromuscular adaptability under higher demands warrant further study.

Clinically, these findings highlight the importance of extending rehabilitation focus beyond early recovery and incorporating running-specific assessments and interventions into later stages of care. Restoration of normal sagittal-plane knee mechanics during running may be a key target for optimizing long-term knee health and functional performance.

Future research should prioritize longitudinal designs, standardized biomechanical protocols, and inclusion of diverse populations to better understand recovery trajectories and inform evidence-based return-to-running guidelines after ACL reconstruction.

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