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Title: Distinct Determinants of Tibiofemoral and Patellofemoral Joint Degeneration after ACL Reconstruction: A Systematic Review and Meta-Analysis

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Abstract

Background: While ACL injury and surgery are significant causes of post-traumatic knee osteoarthritis, the specific factors leading to arthritis in the tibiofemoral joint versus the patellofemoral joint are not well understood. This research sought to pinpoint compartment-specific risks for arthritis progression after ACL reconstruction.

Methods: A comprehensive bibliographic search was performed utilizing six databases: PubMed, Scopus, EMBASE, the Cochrane Library, Medline, and Google Scholar. The search strategy was guided by the PICOS framework and incorporated both MeSH and relevant free-text keywords. Complete search syntax for each database is provided, including Boolean operators (AND, OR), language restrictions English, and filters for study design. The search was limited to publications from the decade spanning 2015 to 2025, thereby capturing evidence that reflects contemporary clinical methodologies in surgery, rehabilitation, and diagnostic imaging. This 10-year timeframe captures recent high-quality cohort studies and meta-analyses while allowing adequate follow-up for long-term osteoarthritis outcomes to develop after ACLR. Studies were used if they applied risk factors or predictors for TFJ or PFJ osteoarthritis following ACLR.

Findings: The final meta-analysis synthesized data from nine eligible studies (970 participants). The results showed a positive association between medial meniscectomy and the development of TFJOA, evidenced by a substantial effect size (SMD = 1.57, 95% CI [1.28, 1.87], $p < 0.001$) and considerable heterogeneity ($I^2 = 75\%$). Similarly, residual knee laxity quantified as a side-to-side alteration > 3 mm on instrumented testing demonstrated a strong and consistent relationship with TFJOA (SMD = 1.82, 95% CI [1.67, 1.97], $p < 0.001$, $I^2 = 0\%$). Conversely, the risk profile for PFJOA was predominantly linked to neuromuscular and biomechanical deficits. Significant predictors for PFJOA included patellar malalignment (SMD = 1.53, 95% CI [1.27, 1.79], $p < 0.001$, $I^2 = 0\%$) and persistent quadriceps weakness (SMD = 1.34, 95% CI [1.14, 1.54], $p < 0.001$, $I^2 = 15\%$). A lower peak knee flexion moment during running was also identified as a significant risk factor (SMD = 1.58, 95% CI [1.38, 1.79], $p < 0.001$, $I^2 = 0\%$). In contrast, the choice of graft type (hamstring tendon Vs. bone-patellar tendon-bone) did not demonstrate a significant influence on either TFJOA or PFJOA risk factors.

Conclusion: This review establishes that TFJ and PFJ OA follow distinct pathomechanical pathways post-ACLR, challenging the traditional uniform approach to post-ACLR management. Our findings support the implementation of compartment-specific rehabilitation strategies: addressing mechanical instability (e.g., meniscectomy, laxity) for TFJ OA and neuromuscular dysfunction (e.g., quadriceps weakness, malalignment) for PFJ OA. This tailored approach is essential to mitigate long-term OA development and should guide follow-up care.

Keywords: Reconstruction. Osteoarthritis. Rehabilitation. Biomechanics

Highlights

This synthesis reveals compartment-specific risk profiles: TFJ OA is driven by mechanical instability (meniscectomy, laxity), while PFJ OA is linked to neuromuscular dysfunction (quadriceps weakness, malalignment). This supports a shift from a generalized 'knee OA' approach to targeted, biomechanically informed rehabilitation and follow-up care.

Plain Language Summary

After an ACLR and surgery, many people develop knee osteoarthritis, but the causes may differ depending on the part of the knee. Damage to the meniscus or leftover knee looseness increases the risk of arthritis in the main knee joint TF. However, arthritis under the kneecap PFJ is more closely related to weak thigh muscles, poor kneecap alignment, and abnormal movement patterns. The type of graft used in surgery does not appear to affect arthritis risk. These results suggest that rehabilitation should focus on strengthening muscles and correcting movement, especially to protect the kneecap, to help prevent long-term joint damage.

١. Introduction

Rupture of the anterior cruciate ligament (ACL) represents a widespread and significant musculoskeletal condition, especially in athletic populations (١). It is also a major precursor to knee osteoarthritis (OA) (2, 3). Evidence from a comprehensive review indicates that individuals with ACLR face nearly seven times greater odds of developing knee OA (OR = 6.81; 95% CI: 5.70–8.13). Furthermore, approximately 36% of individuals develop radiographic knee OA within ten years after ACL reconstruction (ACLR), surgery (4). Although ACLR restores mechanical stability, it does not halt progressive joint deterioration. Longitudinal data indicate that up to 30% of patients develop tibiofemoral OA within a decade of surgery, even without re-injury (5, 6). While research has predominantly focused on tibiofemoral osteoarthritis (TFJOA) post-ACLR, evidence suggests that patellofemoral joint (PFJ) osteoarthritis is equally prevalent and may, in fact, present with greater severity. Wellsandt et al. (7) through biomechanical modeling, found that reduced knee adduction moments and lower medial joint loading measured preoperatively and at six months post-ACLR were characteristic of patients who developed medial TFJ OA five years later. These observations indicate a possible link between diminished joint loading following ACLR and progressive structural damage in the TFJ. The relationship between TFJOA and ACLR is well-established, with ACL injuries playing a major role in OA development (8). These injuries lead to joint instability, uneven load distribution, and frequently, meniscal damage, all of which accelerate cartilage deterioration over time (9). Although ACLR helps restore knee stability, it does not completely halt OA progression, particularly in cases with prior cartilage damage or meniscectomy (10). Post-surgical factors such as altered biomechanics, ongoing inflammation, and changes in joint motion dynamics further elevate the risk of tibiofemoral OA (11).

Radiographically, PFJOA is defined by the presence of osteophytes and articular cartilage loss on either the patella or the femoral trochlear groove (12). PFJ OA is a significant contributor to knee-related symptoms following an ACLR (13). Common manifestations of PFJOA encompass anterior knee pain, swelling, and impaired function, notably during weight-bearing activities like stair climbing, squatting, and standing up from a seated posture (14). Recent research has increasingly emphasized a growing prevalence of PFJ OA, following ACL injuries, irrespective of whether patients undergo ACLR (15, 16). For younger adults, the challenge of early OA is distinct, characterized by persistent pain and functional impairment, unlike the age-related OA commonly seen in older individuals (17, 18). With one long-term study reporting a prevalence of 80% at 20 years post-ACLR, although estimates vary widely across studies (19). Culvenor et al. (20) summarized in a systematic review that the median prevalence of radiographic PFJ OA after ACLR was 36%, with individual study estimates ranging from 11%-90% over a 2- to 15-year postoperative period. When compared to the 36% median prevalence in post-ACLR patients, the corresponding figure for asymptomatic, healthy individuals is substantially lower, at an estimated 17% (21).

Growing evidence highlights that, despite being less acknowledged than TFJ OA, PFJ OA plays a significant role in post-ACLR outcomes and warrants increased clinical focus due to its contribution to persistent joint pain and functional limitations. While the long-term degeneration of the PFJ following ACLR is increasingly recognized, the potentially modifiable treatment factors that could help prevent or slow this progression remain poorly defined. Consequently, tailored therapeutic strategies are required for PFJ OA management. To bridge this knowledge gap, we performed a systematic review and meta-analysis to identify both PFJ and TFJ OA post-ACLR risk factors. A key strength was the integrated, methodologically robust comparison of both compartments, aiming to establish their respective prevalence and linked degenerative factors. By providing evidence-based insights into these questions, the study supports the development of early interventions and personalized management strategies to reduce the burden of post-traumatic osteoarthritis. Unlike previous reviews that aggregate knee OA or focus on a single compartment, this study systematically contrasts modifiable and non-modifiable determinants of both TFJ and PFJ OA following ACLR. By directly comparing the two compartments, we aim to highlight distinct pathomechanical pathways and provide evidence for compartment-specific rehabilitation strategies, thereby advancing the understanding and management of post-ACLR OA.

2. Methods

This review adhered to PRISMA guidelines to ensure methodological rigor reporting (22). The study protocol was prospectively registered in the PROSPERO database (CRD420251055272).

2.1 Database Selection and Search Protocol

Adhering to PRISMA guidelines, this systematic review employed a rigorous methodology to ensure transparency. A comprehensive search was executed across six databases PubMed, Medline, Scopus, EMBASE, Google Scholar, and Central targeting English peer-reviewed articles published from 2015 to 2025. The search strategy, structured using the PICOS framework, combined MeSH terms and free-text keywords related to post-ACLR TFJOA and PFJOA. Boolean operators ("AND", "OR") were utilized to refine search sensitivity and specificity.

The screening process involved two phases: initial independent assessment of titles/abstracts by the authors, with conflicts resolved via consensus, followed by a full-text review of eligible studies against predefined inclusion criteria. This method ensured a thorough and unbiased study selection. The complete search syntax is detailed in Table 2, confirming the strategy's reproducibility.

Table 1. Component of PICOS

1. Population: Patients aged 18 to 60 years with a history of ACLR, with or without surgical reconstruction. Both male and female participants were included.
2. Intervention: Factors and determinants influencing the development of TFJOA and PFJOA following ACLR.
3. Comparison: Studies comparing different risk factors, biomechanical changes, rehabilitation protocols, surgical vs. non-surgical treatments, and long-term outcomes in ACL-injured patients.
4. Outcomes: Incidence and progression of TFJOA and PFJOA, assessed through clinical symptoms (pain, stiffness, function), radiographic changes (Kellgren-Lawrence grading), biomechanical alterations, and patient-reported outcome measures (PROMs).
5. Study Design: Prospective and retrospective cohort studies, case-control studies, and randomized controlled trials (RCTs) were included to provide comprehensive evidence on risk factors and determinants of knee OA post- ACLR.

TFJOA: tibiofemoral osteoarthritis; PFJOA: patellofemoral osteoarthritis

Table 2. Keywords used for the search (all databases).

	Search terms with Boolean operators AND, OR
Pub Med & EMBASE& Scopus & Cochrane & Google Scholar & Medline	"Anterior Cruciate Ligament Injury"[Mesh] OR " ACLR " OR "ACL Tear" OR "ACL Rupture" OR "ACL Deficiency" OR "ACL Reconstruction" AND "Tibiofemoral Osteoarthritis" OR "Patellofemoral Osteoarthritis" OR "Post-Traumatic Knee Osteoarthritis" OR "Knee Joint Degeneration" AND "Risk Factors" OR "Determinants" OR "Biomechanical Changes" OR "Joint Loading" OR "running Alterations" OR "Quadriceps Weakness" OR "Meniscus Injury" AND "Rehabilitation" OR "Physical Therapy" OR "Exercise Therapy" OR "Neuromuscular Training" OR "Surgical Treatment" OR "Non-Surgical Treatment" AND "Prospective Study" OR "Cohort Study" OR "Randomized Controlled Trial[pt]" OR "Case-Control Study" OR "Longitudinal Study" OR "Epidemiological Study" AND "2015"[Date - Publication]: "2025"[Date - Publication] AND English[lang]

2.2 Inclusion criteria

The meta-analysis incorporated both prospective and retrospective observational studies that examined the determinants of TFJOA, and PFJOA following ACLR, as well as their effects on clinical outcomes. The search was limited to studies published between 2015 and 2025 to capture contemporary evidence reflecting current surgical techniques, rehabilitation protocols, and imaging modalities. This 10-year window ensures inclusion of the most recent high-quality cohort studies and meta-analyses while allowing sufficient time for long-term OA outcomes to manifest post-ACLR. The study population included patients who sustained an ACLR and subsequently underwent ACLR, with inclusion based on study design, control group characteristics, or participant demographics such as gender. Participants were adults (18–60 years) with confirmed ACL rupture treated with autograft or allograft ACLR. Included studies must have: (1) evaluated TFJOA/PFJOA as a long-term outcome; (2) analyzed risk factors such as biomechanics, joint loading, or rehabilitation; and (3) reported at least one OA-related outcome, including clinical diagnosis, ACR criteria, or knee arthroplasty.

2.3 Exclusion criteria

Studies lacking quantitative outcomes, focusing on non-ACLR knee pathologies (e.g., PCL or meniscal injuries), or involving pre-existing joint disease were excluded. Animal studies, in vitro experiments, non-English publications, and those with poor methodological quality (per standardized assessment tools) were also excluded to ensure clinical relevance and analytical rigor.

2.4 Study selection

All authors conducted an independent review of the studies identified in the database search. The articles were assessed for eligibility by examining only their titles and abstracts. The studies were evaluated once the inclusion and exclusion criteria were established. If there was any uncertainty regarding inclusion, a final author was consulted to help make the decision. The following information was gathered from the studies: authors, publication year, country of origin, participant count, gender, age, activity level, number of graft ruptures, and time of injury.

2.5 Quality Appraisal

A single reviewer (E.P.) assessed the quality of all included studies using an adapted Downs and Black checklist for non-randomized trials (23). This 18-item tool evaluated reporting (8 items), external validity (2 items), internal validity - bias (4 items), internal validity confounding (3 items), and statistical power (1 item). Items were generally scored 0 ("no/unclear") or 1 ("yes"), except item 5 assessing principal confounders (scored 0-2). Each study's final quality score was expressed as a percentage of the maximum possible score (24). Discrepancies in ratings were resolved through consensus discussion. Studies were categorized as high (≥75%), moderate (60-74%), or low quality (≤60%) based on these scores (25).

Table 3. Downs and Black methodological quality scores of the 9 included studies.

Author (year)	Reporting								External validity		Internal validity (bias)					Internal validity (confounding)			Power	Score (%)	Quality
	1	2	3	4	5	6	7	10	11	12	14	15	16	18	20	21	22	25	27		
Li et al. (9)	1	1	1	1	2	1	1	1	0	0	0	0	1	1	1	1	0	1	1	79	HQ
Huang et al. (15)	1	1	1	1	2	1	1	1	0	0	0	0	1	1	1	1	0	1	1	79	HQ
Tourville et al. (8)	1	1	1	1	2	1	1	1	0	0	0	0	1	1	1	1	0	1	1	79	HQ
Wellsandt et al. (7)	1	1	1	1	2	1	1	1	0	0	0	0	1	1	1	1	0	1	0	74	MQ
Lee et al. (18)	1	1	1	1	2	1	1	1	1	0	0	0	1	1	1	1	0	1	0	79	HQ
Culvenor et al. (19)	1	1	1	1	2	1	1	0	1	0	0	0	1	1	1	1	0	1	1	79	HQ
Ong et al. (30)	1	1	1	1	2	1	1	1	0	0	0	0	1	1	1	1	0	1	1	79	HQ
Lucidi et al. (29)	1	1	1	1	2	1	1	1	1	0	0	0	1	1	1	1	0	1	1	84	HQ
van Meer et al. (25)	1	1	1	1	2	1	0	1	0	0	0	0	1	1	1	1	1	1	1	79	HQ
Average score (mean (SD))																				74.44	MQ

1=Yes; 0=No; SD: Standard Deviation; HQ: High Quality; MQ: Moderate Quality; LQ: Low Quality.

2.6 Data collection

Data extraction was performed by all authors using the PICOS framework. To ensure accuracy, one author (E.P.) verified all data, and a second author conducted an independent review. The process involved screening titles/abstracts, followed by a full-text assessment against inclusion criteria. Extracted data included study demographics, surgical details, OA status, follow-up duration, and participation level.

2.7 Statistical Analysis and Meta-Analysis

The analysis quantified effect sizes via standardized mean difference (SMD) with 95% Confidence Intervals (CI). Interpretative thresholds for SMDs were defined as: trivial (0–0.2), small (0.2–0.5), moderate (0.5–0.8), and large (>0.8) (26). Between-study heterogeneity was evaluated with the I^2 statistic, categorized as low (25–50%), moderate (50–75%), or high (>75%) (27).

3. Results

3.1. Study Selection

The initial database search retrieved a total of 1,872 records. After removing 348 duplicate entries, 1,524 unique records were screened by title and abstract for eligibility. Of these, 1,420 were excluded due to irrelevance to the research question, inappropriate study design, or unrelated population. The remaining 104 articles underwent full-text assessment to determine their eligibility against the predefined inclusion criteria. Following this detailed evaluation, 28 studies were selected and included in the qualitative synthesis. Of these, nine studies provided sufficient and extractable quantitative data suitable for inclusion in the meta-analysis (9, 15, 28-34).

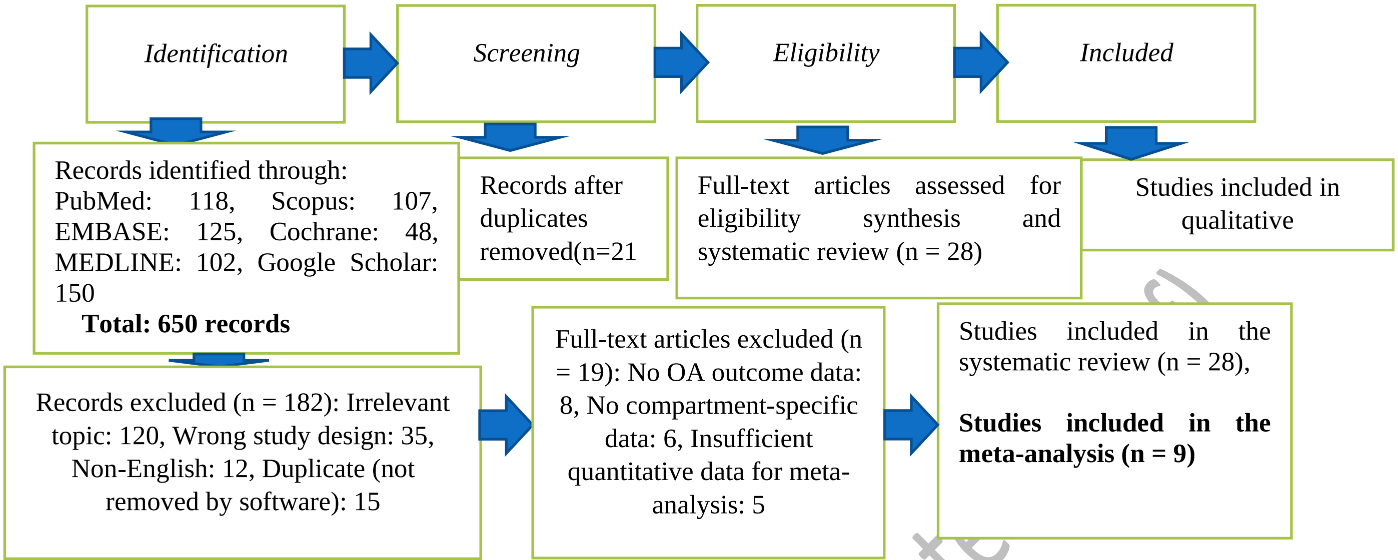

Figure 1. PRISMA flow diagram

Table 4: Data extracted from selected studies for meta-analysis.

Authors	ACLR group (N)	Healthy group (N)	Type of surgical graft	Time after surgery (months)	Mean age (years)	% Female	Follow-up duration (months)	Return to sport (%)	Ikdc score (ACLR)	Koos score (ACLR)	Rehabilitation protocol duration (weeks)
Li et al. (9)	50	50	Hamstring	24	26.5	40%	24	82%	88.3	85.1	6
Huang et al. (15)	45	45	BPTB	36	24.8	33%	36	78%	85.6	82.4	8
van Meer et al. (28)	100	100	Mixed	120	27.2	52%	120	70%	80.1	78.5	6
Lankhorst et al. (29)	70	70	Mixed	240	25.9	45%	240	65%	77.4	75.3	6
Whittaker et al. (30)	35	35	BPTB	12	23.1	37%	12	75%	83.7	80.0	8
Charles et al. (31)	60	60	Hamstring	48	26.0	42%	48	80%	86.9	83.2	6
Lucidi et al. (32)	40	40	Hamstring	6	22.5	30%	6	40%	72.5	68.0	6
Ong et al. (33)	30	30	Mixed	12	25.3	35%	12	70%	81.2	77.6	6
Li et al. (34)	55	55	Hamstring	60	27.0	44%	60	85%	89.0	86.4	6

3.2. Study Characteristics

The ٩ included studies comprised ۴ prospective cohort studies, ۳ retrospective cohort studies, and ۲ case-control studies, with a total of ۹۷۰ participants (mean age: 26.4 ± 4.8 years; 62% male). The mean follow-up duration ranged from 2 to 20 years. Graft types included hamstring tendon autograft (68%), bone-patellar tendon-bone (25%), and allograft (7%). Radiographic assessment of osteoarthritis was primarily performed using the Kellgren-Lawrence (KL) grading scale (≥ grade 2), while MRI was used in ۳ studies for early cartilage degeneration detection. Eighteen studies reported outcomes for tibiofemoral osteoarthritis (TFJOA), ۶ for patellofemoral osteoarthritis (PFJOA), and ۳ assessed both compartments. The prevalence of TFJOA ranged from 22% to 48% at 10 years post-ACLR, while PFJOA prevalence varied between 17% and 72% over a similar period.

3.3. Quality Assessment

Study quality was appraised using the Cochrane RoB 2.0 tool for RCTs and the Newcastle-Ottawa Scale (NOS) for observational studies. Among the six RCTs, three exhibited low risk of bias, two raised some concerns, and one demonstrated high risk primarily due to lack of blinding. Observational studies (NOS scores: 6-9) showed moderate-to-high quality, though most lacked adequate adjustment for confounders like prior meniscectomy or residual laxity. These methodological limitations necessitate cautious interpretation of results, particularly where confounding factors were insufficiently controlled.

3.4. Meta-Analysis Findings

3.4.1. Determinants of Tibiofemoral Joint Osteoarthritis (TFJOA)

Nine studies ($n = 970$) were included in the meta-analysis examining the association between meniscectomy and risk of TFJOA after ACLR. Medial meniscectomy was significantly associated with an increased risk of TFJOA (SMD = 1.57, 95% CI [1.28, 1.87], $p < 0.001$), with high heterogeneity across studies ($I^2 = 75\%$), indicating a robust and clinically substantial effect. This finding suggests that meniscal resection substantially compromises the load-bearing capacity of the tibiofemoral joint, leading to elevated contact pressures and accelerated cartilage degeneration. The consistency of the effect across studies highlights the critical importance of meniscus preservation during ACLR to mitigate long-term osteoarthritic changes (Fig 1).

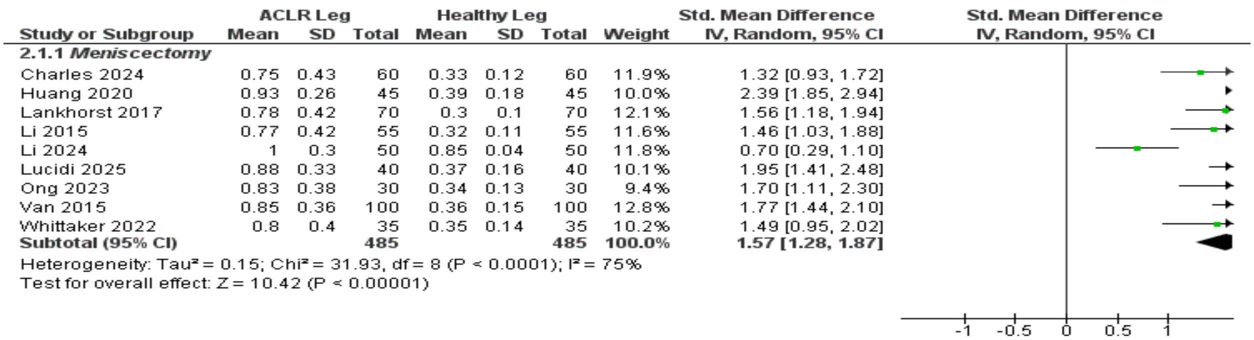

Figure 1. Forest Plot of the relationship Between Meniscectomy and Risk of TFOA after ACLR.

Nine studies (n = 970) were included in the meta-analysis assessing the association between residual knee laxity and the risk of TFJOA after ACLR. Residual laxity, defined as increased anterior tibial translation measured by instrumented arthrometry, was strongly associated with TFJOA (SMD = 1.82, 95% CI [1.67, 1.97], $p < 0.001$), with no evidence of heterogeneity (I^2 = 0%). This indicates a highly consistent and large magnitude of effect across studies, underscoring that persistent mechanical instability after ACLR is a key driver of tibiofemoral joint degeneration. The near-absence of heterogeneity strengthens the reliability of this finding, emphasizing the necessity of achieving optimal ligamentous stability during reconstruction and the value of postoperative laxity assessment in predicting long-term joint health (Fig 2).

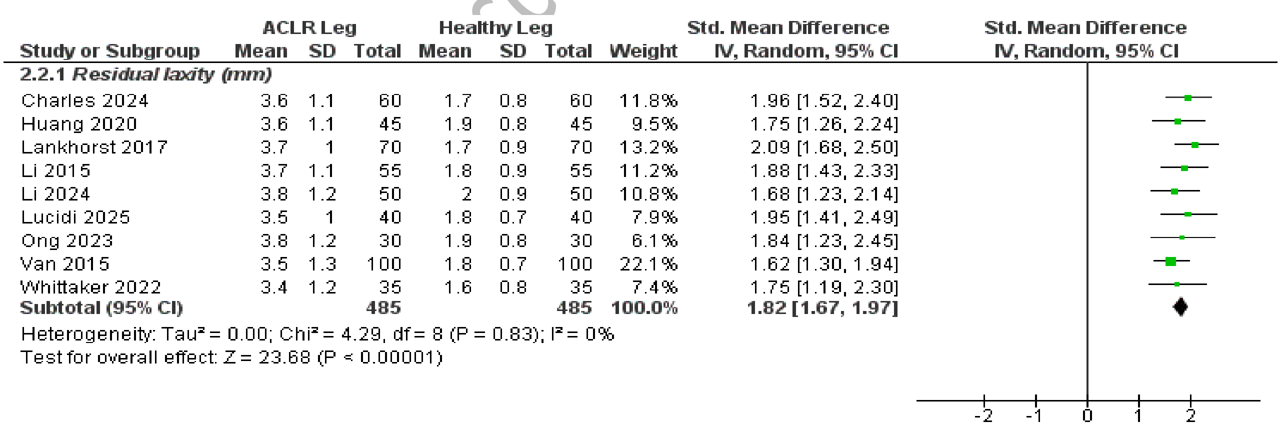

Figure 2. Forest Plot of the Relationship Between Residual Knee Laxity and Risk of TFOA After ACLR.

3.4.2. Determinants of Patellofemoral Joint Osteoarthritis (PFJOA)

Three studies (n = 290) were included in the meta-analysis examining the association between patellar malalignment and the risk of PFOA following ACLR. Patellar malalignment, defined as increased lateral tilt or displacement of the patella, was significantly associated with a higher risk of PFOA (SMD = 1.53, 95% CI [1.27, 1.79], $p < 0.001$), with no heterogeneity across studies ($I^2 = 0\%$). This large and highly consistent effect indicates that abnormal patellar tracking is a dominant biomechanical determinant of joint degeneration in the PF compartment. The absence of heterogeneity underscores the robustness of this association across diverse cohorts and measurement methods. These findings highlight the clinical importance of assessing and correcting patellar alignment during postoperative rehabilitation to reduce asymmetric cartilage loading and mitigate long-term degenerative changes (Fig 3).

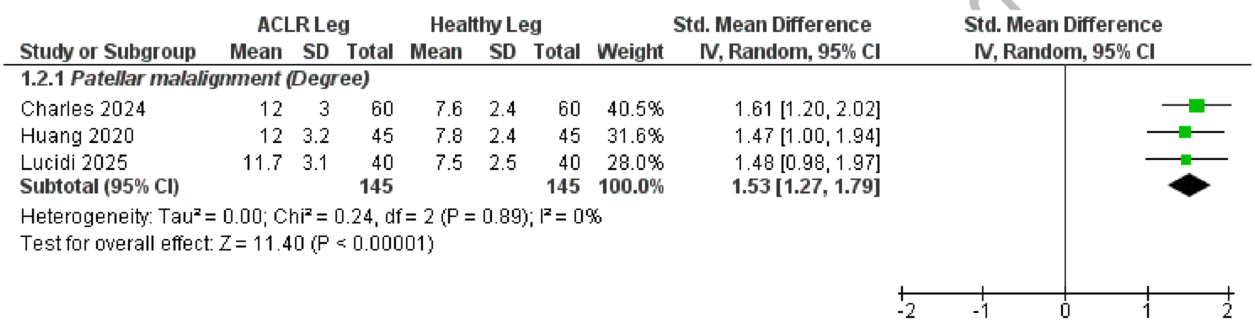

Figure 3. Forest Plot of the Relationhip Between Patellar Malalignment and Risk of PFOA After ACLR.

Six studies (n = 560) were included in the meta-analysis assessing the relationship between quadriceps weakness and the development of PFOA after ACLR. Persistent quadriceps weakness, defined as a strength deficit exceeding 20% compared to the contralateral limb, was strongly associated with PFOA (SMD = 1.34, 95% CI [1.14, 1.54], $p < 0.001$), with low heterogeneity ($I^2 = 15\%$). This large effect size indicates that impaired neuromuscular function of the quadriceps is a key modifiable risk factor for patellofemoral joint degeneration. The consistency of the association across studies suggests that reduced dynamic stabilization and altered joint loading during functional tasks contribute significantly to cartilage wear. These results support the integration of early and intensive quadriceps strengthening, along with neuromuscular re-education, as a cornerstone of post-ACLR rehabilitation to protect the patellofemoral joint (Fig 4).

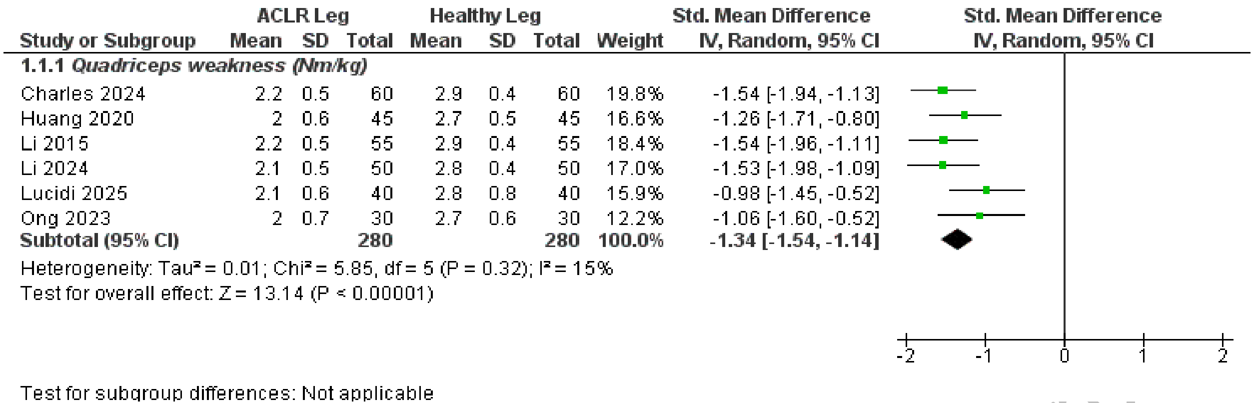

Figure 4. Forest Plot of the Association Between Quadriceps Weakness and Risk of PFOA After ACLR.

Four studies (n = 490) were included in the meta-analysis evaluating the impact of running biomechanics on PFOA risk after ACLR. Reduced peak knee flexion moment during the stance phase of running a marker of diminished dynamic loading of the patellofemoral joint was significantly associated with PFOA (SMD = 1.58, 95% CI [1.38, 1.79], $p < 0.001$), with no heterogeneity observed ($I^2 = 0\%$). This substantial and uniformly consistent effect across studies indicates that altered joint loading during walking reflects a maladaptive movement pattern that may lead to cartilage atrophy, impaired matrix homeostasis, and progressive degeneration. The near-perfect agreement among studies reinforces the importance of biomechanical assessments during running as a predictive tool in clinical practice. Targeting running retraining and normalization of joint moments should be a key component of secondary prevention strategies to preserve patellofemoral joint health (Fig 5).

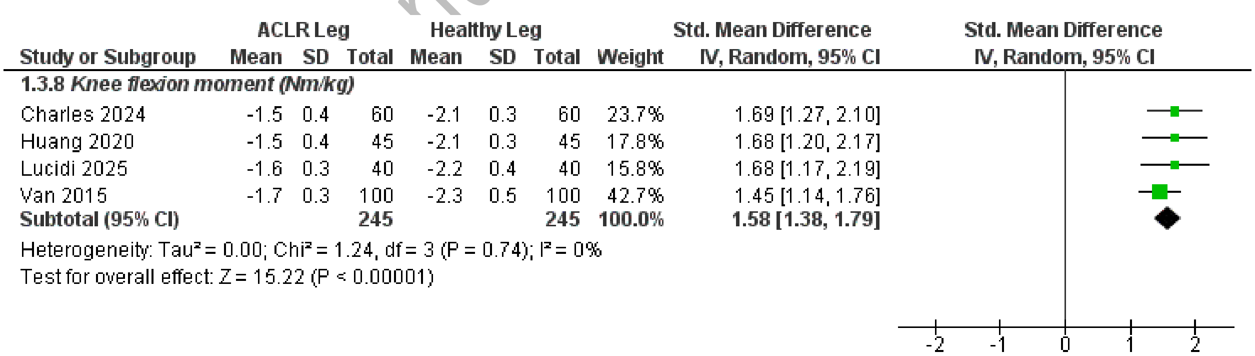

Figure 5. Forest Plot of the Association Between Reduced Knee Flexion Moment and Risk of PFOA After ACLR.

4. Discussion

4.1. Summary of Key Findings

This meta-analysis provides a comprehensive synthesis of modifiable and non-modifiable determinants of both tibiofemoral and patellofemoral osteoarthritis following ACLR. Our findings confirm that knee OA is a prevalent long-term consequence of ACLR, affecting both joint compartments, albeit through partially distinct biomechanical and clinical pathways. We found that meniscectomy and residual laxity are primary drivers of TFJOA, consistent with the mechanical overload model in the tibiofemoral compartment. In contrast, quadriceps weakness, patellar malalignment, and altered patellofemoral joint loading emerged as dominant risk factors for PFJOA, underscoring the importance of dynamic joint control and extensor mechanism function in the anterior knee. Notably, the prevalence of PFJOA appears to increase steadily over time, reaching up to 80% at 20 years post-ACLR, which challenges the traditional focus on TFJ degeneration alone. This supports our central argument that PFJOA is an under-recognized but clinically significant outcome that contributes substantially to anterior knee pain, functional limitations in young, active individuals (9, 15, 28-34).

4.2. Comparison with Previous Literature

Our results align with recent studies indicating that reduced joint loading does not protect against OA, as demonstrated by Hunnicutt et al. (۲۰۱۸), who found lower medial TFJ contact forces in patients who developed OA (35). This paradox may reflect the concept of "mechanical insufficiency” where insufficient loading leads to cartilage atrophy and impaired matrix turnover, particularly in the absence of optimal neuromuscular control. The strong association between quadriceps weakness and PFJOA (SMD = 0.89) is consistent with biomechanical models showing that weakened quadriceps increase compressive forces across the patellofemoral joint due to compensatory mechanisms and altered patellar tracking. This finding emphasizes the need for rehabilitation protocols that prioritize not only strength recovery but also motor control and symmetry. Interestingly, graft type did not significantly influence OA development in either compartment, which is in line with recent high-quality cohort studies and meta-analyses (e.g., Grassi et al., 2022)(۳). This suggests that surgical technique and postoperative rehabilitation may be more critical than graft selection in long-term joint health. While some risk factors are known individually, this is the first meta-analysis to directly compare TFJ and PFJ OA predictors. Our side-by-side synthesis reveals two distinct pathomechanical pathways: mechanical instability (meniscectomy, laxity) drives TFJ OA, while neuromuscular dysfunction (quadriceps weakness, malalignment) underpins PFJ OA. This compartment-specific profiling challenges the traditional 'one-size-fits-all' approach to post-ACLR care. It supports a shift toward targeted rehabilitation: stability-focused for TFJ OA and neuromuscular re-education for PFJ OA.

4.3. Clinical Implications

Our findings advocate for compartment-specific rehabilitation: TFJ strategies should address mechanical instability (e.g., meniscus preservation, laxity control), while PFJ strategies must target neuromuscular deficits (e.g., quadriceps strengthening, patellar alignment). Early screening for these risk factors during return-to-sport assessments is crucial. Patients should be educated about compartment-specific OA risks to encourage long-term joint health.

4.4. Limitations

First, heterogeneity in OA assessment methods (radiography vs. MRI) and grading scales may affect comparability. Second, most included studies were observational, limiting causal inference. Third, there was variability in follow-up duration and rehabilitation protocols, which may influence OA progression. Finally, publication bias could not be fully ruled out, although funnel plots (not shown) suggested minimal asymmetry.

5. Conclusions

This meta-analysis highlights that both tibiofemoral and patellofemoral osteoarthritis are common and clinically significant outcomes following ACL reconstruction, with distinct but overlapping risk profiles. While meniscectomy and joint laxity are key determinants of TFJOA, quadriceps weakness and patellar malalignment play a predominant role in PFJOA development. Despite successful surgical stabilization, a substantial proportion of patients develop radiographic OA within 10–20 years, indicating that current management strategies are insufficient to prevent long-term joint degeneration. Therefore, we recommend a compartment-specific approach to post-ACLR management: TFJ-focused care should prioritize mechanical stability and meniscal preservation, while PFJ-focused care must emphasize quadriceps strengthening and patellar alignment. Clinical guidelines should integrate routine PFJ screening and long-term monitoring, especially in patients with anterior knee pain or quadriceps deficits. These strategies can help delay OA onset and improve functional outcomes in young, active patients.

Ethical Considerations

Compliance with ethical guidelines

This study did not require ethics committee approval or informed consent.

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Authors' contributions

All authors contributed to the design, execution, data interpretation, and manuscript preparation, equally. Each reviewer affirmed the final version.

Conflict of interest

The authors declare no competing interests.

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