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Systematic Review

Increased posterior tibial slope is a risk factor for anterior cruciate ligament injury and graft failure after reconstruction: A systematic review

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ABSTRACT

Importance: Anterior cruciate ligament (ACL) injury and ACL reconstruction (ACLR) graft failure are important clinical concerns that result in long recovery periods, potential long-term knee instability, and poor patient outcomes. Identifying risk factors such as posterior tibial slope (PTS), meniscal slope (MS), and meniscal bone angle (MBA) is important for improving risk stratification, guiding management decisions, and reducing the incidence of both ACL injury and ACLR graft failure.
Objective: This systematic review and meta-analysis aim to determine whether increased PTS, increased MS, and decreased MBA serve as independent predictors of both ACL injury and ACLR graft failure.
Evidence review: A comprehensive search of the literature was conducted following Preferred Reporting Items for Systematic Reviews and Meta-analyses (PRISMA) guidelines. For evaluating ACL injury, the review included comparative studies measuring PTS, MS, or MBA between ACL injury patients and ACL-intact controls. For ACLR graft failure, studies comparing these measurements between patients with ACLR graft failures and those with successful ACLR outcomes were included. Data were pooled using a random-effects model to calculate the overall mean difference (MD) between groups.
Findings: Out of 1,683 initially identified studies, 75 studies were selected for detailed analysis, 53 analyzing ACL injury and 24 studies analyzing ACLR graft failure. The meta-analysis revealed that increased PTS significantly increases the risk of both ACL injury (MD 1.64°; 95% CI: 1.08–2.20, $p < 0.01$) and ACLR graft failure (MD 1.76°; 95% CI: 1.03–2.48, $p < 0.01$). This is statistically significant for both lateral and medial PTS, and across both radiograph and magnetic resonance imaging. A higher lateral MS (MD 3.25°; 95% CI: 1.70–4.80, $p < 0.01$) and a lower lateral MBA (MD -3.85°; 95% CI: -6.38–1.32, $p < 0.01$) were also significantly associated with an increased risk of ACL injury. However, no statistically significant differences were observed for MS or MBA between ACLR graft failure and successful ACLR groups.
Conclusion and Relevance: The findings indicate that increased PTS, whether measured medially or laterally, is a statistically significant risk factor for both ACL injury and ACLR graft failure. Additionally, increased lateral MS and decreased lateral MBA are associated with ACL injury. This evidence supports the consideration of tibial slope in risk assessment, preoperative planning, and surgical decision-making for both prevention of ACL injury and ACLR procedures. Further research is necessary to fully understand the role of MS and MBA in ACL injury.
Level of evidence: Level IV; systematic review of level III-IV studies.

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What is already known?

- Increased posterior tibial slope is recognised as a statistically significant risk factor for anterior cruciate ligament injuries and reconstruction graft failure, with its role being increasingly studied.
- Biomechanical differences between lateral and medial slopes have highlighted their distinct roles in anterior cruciate ligament injury risk, leading to a focused examination of their individual impacts.
- Meniscal slope and meniscal bone angle are emerging as contributors to anterior cruciate ligament injury and graft failure risk that may either potentiate or reduce the risk associated with increased posterior tibial slope.

What are the new findings?

- Both increased lateral and medial posterior tibial slopes are statistically significant risk factors for anterior cruciate ligament injury and reconstruction graft failure, with lateral posterior tibial slope showing a stronger association.
- A higher lateral meniscal slope and lower lateral meniscal bone angle are significantly associated with an increased risk of anterior cruciate ligament injury, with no statistically significant difference observed in medial meniscal slope or medial meniscal bone angle.
- Meniscal slope and meniscal bone angle were not statistically significant predictors of anterior cruciate ligament reconstruction graft failure.

INTRODUCTION

Identifying risk factors for anterior cruciate ligament (ACL) injury and ACL reconstruction (ACLR) graft failure is important to improve injury prevention algorithms and guide surgical interventions. Increased posterior tibial slope (PTS) has been identified as a potentially important risk factor for both ACL injury and ACLR graft failure [1,2]. Recent studies have also highlighted the potential contribution of the meniscus to the functional slope [3–5].

Biomechanically, a higher tibial slope in the presence of a compressive load generates a greater anterior shear component of the tibiofemoral reaction force [6]. This results in increased anterior motion of the tibia relative to the femur and, consequently, a greater load on the ACL [6]. Studies have reported a linear relationship between PTS and strain on both native ligaments and reconstructed ACL grafts [7–9]. As a risk factor for ACLR graft failure, PTS is modifiable through osteotomy and has traditionally been recommended for second and third revisions [10,11]. However, it is increasingly being performed during first revision ACLR cases [1,12].

Recent research also suggests that the meniscus may influence the functional slope [3–5]. The medial meniscus, in particular its posterior horn, represents an important secondary stabiliser of anterior tibial translation under an anterior-posterior tibial load, while the lateral meniscus has an important role as a restraint of rotational and dynamic laxity [13], also reducing ACL strain [14].

The relationship between PTS, meniscal slope (MS), and meniscal bone angle (MBA) with ACL injury has been assessed in several comparative studies, though the findings have been inconsistent [3–5, 15–21]. This study aimed to systematically evaluate whether PTS, MS, and MBA measurements are indicators of increased susceptibility to ACL injury and ACLR graft failure. It was hypothesised that patients who experienced ACL injury would demonstrate increased PTS and MS, and decreased MBA compared with intact native ACL controls, and patients who experienced ACLR graft failure would display similar patterns when compared with intact ACLR graft controls.

METHODS

Search strategy

This study was conducted following the Preferred Reporting Items for Systematic Reviews and Meta-analyses (PRISMA) guidelines. The online databases PubMed, OVID Medline, OVID Embase, and Scopus were searched from inception to 16th October 2024 using the search terms ("anterior cruciate ligament" OR "ACL") AND ("angle" OR "slope") AND (tibia* OR meniscus*). The first four search terms were limited to the title and/or abstract and the overall search was limited to studies conducted on humans and written in the English language. Reference lists of the identified trials were manually searched to identify any additional publications, as well as relevant reviews. Conference programs and abstracts were also searched to identify any ongoing research in this area.

Study eligibility

Inclusion criteria were: 1) levels of evidence IV or greater, 2) skeletally mature patients (age 16 years and/or complete closure of physis reported), 3) comparative studies, prospective or retrospective, 4) studies reporting on a cohort of patients who experienced ACL injury (cases) versus patients with intact ACLs (controls) or patients who experienced ACLR graft failure (cases) versus patients with intact ACLR graft (controls), 5) studies reporting at least one of PTS, MS, or MBA measurements for each group. Studies with the following criteria were excluded: cadaveric studies, technique papers, articles studying nonhuman subjects, studies that did not report an ACL injury population, and studies without a full-text publication available.

Screening

Study selection was conducted independently by two reviewers (C.Z. and F.M.B.). An initial screening of titles and abstracts was performed. Subsequently, full texts of the remaining articles were retrieved and reviewed. Disagreements at the full-text level were resolved by a third reviewer (T.L.).

Data abstraction

Prearranged Excel spreadsheets (Microsoft Corp., Redmond, WA) were structured to collate information from selected studies. Specific details collected included the imaging modality (radiograph or magnetic resonance imaging [MRI]), the measurement technique, the relevant anatomic measurements (medial/lateral tibial slope, medial/lateral meniscal slope, and medial/lateral meniscal bone angle), and the mean and standard deviation of these measurements for each group. Where the standard deviation was not given, this was estimated using Cochrane handbook calculations.

Demographic data were also gathered for each study cohort, encompassing gender, age, time until graft failure, and follow-up duration. Other essential information included the first author's name, publication year, country, cohort sizes, and criteria for assessing ACL integrity and matching control groups.

In cases where studies subdivided cohorts (e.g. by gender, laterality, or number of ACL injuries), and only aggregate data were presented, values were combined prior to extraction. When multiple measurement techniques were available for the same parameter, data from the most commonly used method across studies were selected for consistency. Imaging methods were categorized as either lateral radiograph or MRI.

Quality assessment

The methodological index for nonrandomized studies (MINORS) criteria was used for the quality assessment of the included studies. For each study, each of the 12 items was scored 0 (not reported), 1 (reported but inadequate), or 2 (reported and adequate), for a maximum score of 24 for comparative studies. Scores of 75% and above were considered low risk for bias, scores between 50 and 75% were considered medium risk for bias, and scores of 50% and below were considered high risk for bias. Two independent reviewers (C.Z. and F.M.B.) assessed each study for the risk of bias, and discrepancies were resolved by a third reviewer (T.L.).

Outcome measures

The primary outcomes analyzed were the degree of tibial slope and meniscal angle measurements in the ACL injury group versus the ACL intact group, and in the ACLR reinjury group versus the successful ACLR group (Fig. 1). The values extracted from the medial and lateral tibial plateaus, along with their respective definitions, are listed below:

- **Posterior tibial slope** – the angle between the tangent to the tibial plateau and a tibial anatomic axis
- **Meniscal slope** – the angle between the tangent to the superior meniscal surface and a tibial anatomic axis
- **Meniscal bone angle** – the angle between the tangent to the superior meniscal surface and the tangent to the tibial plateau

Statistical analysis

The variables of interest were assessed using the mean difference (MD), where the mean and standard deviation were used to conduct a random-effects meta-analysis. Forest plots were created using OpenMetaAnalyst (Brown University) to show the pooled estimate of effect for these outcomes. The data for the primary outcome measurements were extracted and pooled according to imaging modality (lateral radiograph or MRI), with separate meta analyses conducted for each. Raw values for the outcome measurements were scaled appropriately where necessary. Statistical heterogeneity was evaluated using the I^2 statistic and given to two decimal places. A p value of less than 0.05 was considered statistically significant.

Fig. 1. Most common measurement methods for posterior tibial slope (PTS), meniscal slope (MS), and meniscal bone angle (MBA) used in the current review. The PTS is measured as the angle between a line connecting the highest points of the anterior and posterior tibial plateau and a line perpendicular to the longitudinal axis of the tibia (LA) or posterior tibial cortex. **A.** PTS measured as described by Brandon et al. [22] **B.** PTS measured as described by Hendrix et al. [23] **C.** PTS measured as described by Hashemi et al. [24] **D.** LA measured as described by Hudek et al. [25] **E.** Lateral PTS (LPTS), the angle between a line orthogonal to the LA (Line A) and the tangent to the lateral plateau (Line B). Lateral MBA (LMBA), the angle between the tangent to the superior meniscal surface (Line C) and Line B, as described by Sturnick et al. [26] **F.** Medial PTS (MPTS), the angle between Line A and the tangent to the medial plateau (Line D). Medial MS (MMS), the angle between Line A and the tangent to the proximal meniscus surface (Line E).

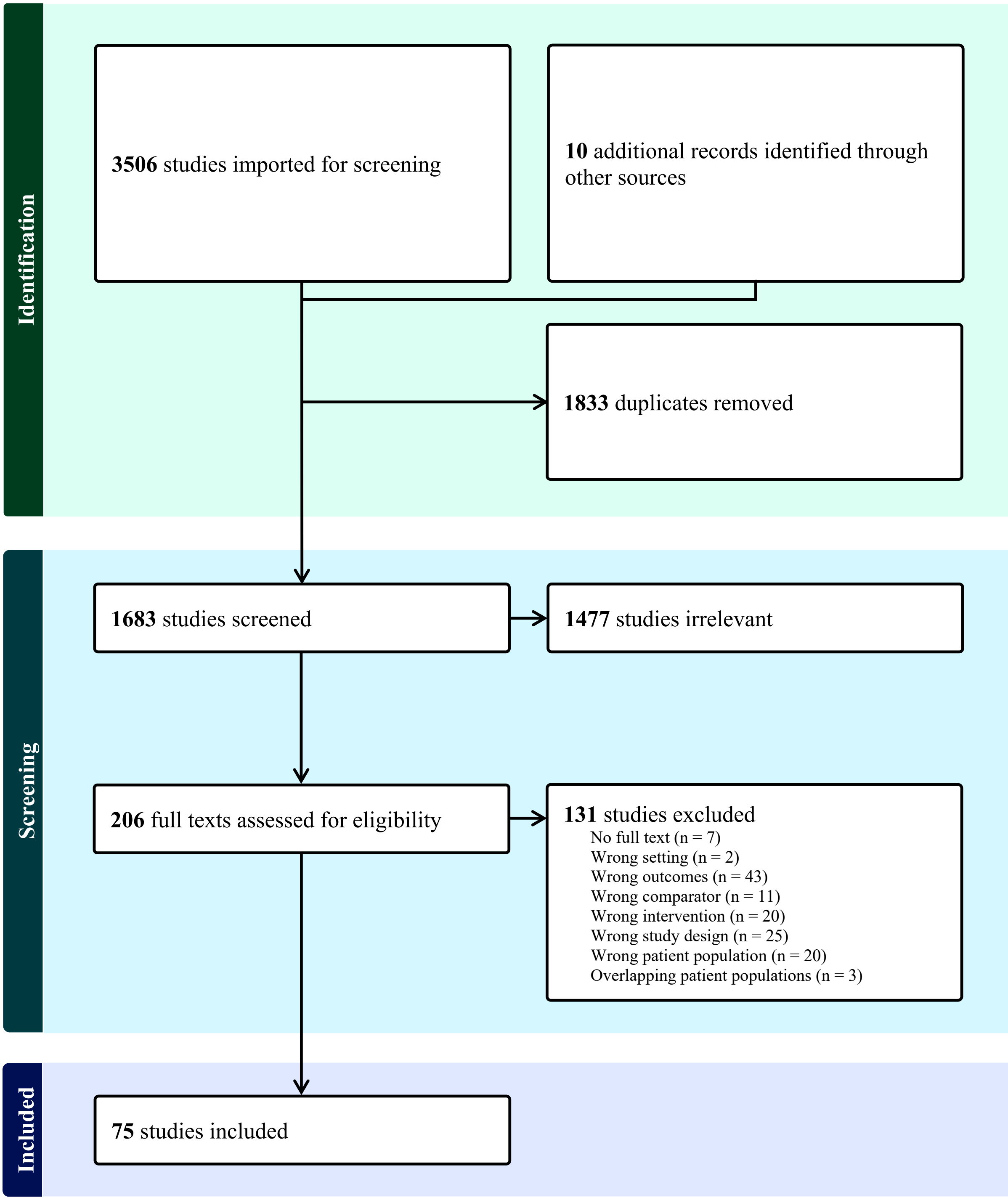

Fig. 2. PRISMA flow diagram indicating the number of studies identified, included and excluded, including reasons for exclusion. PRISMA = Preferred Reporting Items for Systematic Reviews and Meta-analyses.

RESULTS

Search results

The literature search returned 1,673 articles after the exclusion of duplicates (Fig. 2). Ten additional records were identified through reference list searching of included trials and relevant reviews. A total of 75 studies were ultimately included in this review and meta-analysis: 53 analyzing the degree of tibial slope and meniscal slope measurements in an ACL injury group versus an intact ACL control group, and 24 comparing an ACLR graft failure group versus a successful ACLR control group (Table 1). To analyze the risk of ACL injury, 5,353 knees were included in the analysis of the ACL injury group, while 5,058 knees were included in the analysis of the ACL intact control group. To analyse the risk of ACLR graft failure, 1,255 knees were included in the ACLR graft failure group and 4,157 knees in the analysis of the successful ACLR control group.

Risk of bias assessment

The MINORS criteria was used to evaluate the quality and risk of bias for each of the included studies. Out of 75 studies, 51 studies were considered a low risk of bias, and 24 studies were considered a medium risk of bias.

Table 1
Characteristics of included studies.

Author (Year)	Country	Study design	Imaging modality	Measurement method for posterior tibial slope	Injury assessed	Number of knees included		Mean follow-up period for successful ACLR group (months)
						Injury group	Control group	
Beynnon (2014) [27]	USA	Case–control	MRI	Hashemi	ACL injury	88	88	
Bisson (2010) [28]	USA	Case–control	MRI	Hashemi	ACL injury	40	40	
Blanke (2016) [29]	USA	Case–control	MRI	Hudek	ACL injury	80	41	
Bojicic (2017) [30]	USA	Case–control	MRI	Hudek	ACL injury	76	42	
Brandon (2006) [22]	USA	Case–control	LR	Longitudinal (lines)	ACL injury	100	100	
Calek (2024) [31]	Australia	Case–control	MRI	Hashemi	ACLR graft failure	54	57	12
Choi (2023) [32]	Korea	Cross-sectional	MRI	Hudek	ACL injury	207	86	
Christensen (2015) [33]	USA	Case–control	MRI	Hashemi	ACLR graft failure	35	35	82.8
Cruz (2022) [34]	USA	Cohort	LR	Longitudinal (lines)	ACLR graft failure	16	84	126[a]
Dæhlin (2022) [35]	USA	Case–control	LR	Longitudinal (lines)	ACL injury	728	499	
Digiacomo (2018) [17]	USA	Case–control	MRI	Hudek	ACL injury + ACLR graft failure	28/14[b]	10/14[b]	NS
Duerr (2022) [36]	USA	Case–control	LR + MRI	Longitudinal (circles) + Hudek	ACLR graft failure	38	38	74.4
Elmansori (2017) [3]	France, Australia	Case–control	MRI	Hashemi	ACL injury	100	100	
Fares (2022) [20]	France	Case–control	MRI	Hohmann (posterior tibial cortex)	ACLR graft failure	94	94	76.8
Grassi (2019) [37]	Italy	Case–control	MRI	Other	ACLR graft failure	43	43	36
Gultekin (2023) [38]	Turkey	Case–control	MRI	Other	ACL injury	100	100	
Gupta (2020) [39]	India	Case–control	LR	Longitudinal (lines)	ACLR graft failure	64	64	28.2
Gwinner (2021) [40]	Germany	Cohort	LR	Longitudinal (lines)	ACLR graft failure	87	260	NS
Hashemi (2010) [24]	USA, Canada	Case–control	MRI	Hashemi	ACL injury	49	55	
He (2022) [41]	China	Case–control	MRI	Hudek	ACL injury	58	58	
Hendrix (2017) [23]	USA	Case–control	LR	Longitudinal (circles)	ACL injury	100	50	
Hinz (2023) [21]	Germany	Case–control	LR	Longitudinal (circles)	ACLR graft failure	52	274	71[c]
Hohmann (2011) [42]	Australia	Case–control	LR	Posterior tibial cortex	ACL injury	272	272	
Hohmann (2021) [43]	South Africa	Case–control	MRI	Other	ACL injury	159	192	
Huang (2019) [44]	China	Case–control	MRI	Other	ACL injury	52	52	
Hudek (2011) [45]	Switzerland	Case–control	MRI	Hudek	ACL injury	55	55	
Ikawa (2021) [46]	Brazil	Case–control	MRI	Hudek	ACL injury	59	61	
Jaecker (2018) [47]	Germany, USA	Case–control	MRI	Hashemi	ACLR graft failure	57	69	62.28
Jagadeesh (2022) [48]	India	Randomised controlled trial	LR + MRI	Longitudinal (lines) + other	ACL injury	60	60	
Jeon (2022) [49]	South Korea, USA	Case–control	LR	Longitudinal (lines)	ACL injury	59	58	
Khan (2011) [50]	South Korea	Case–control	MRI	Hashemi	ACL injury	73	51	
Kizilgoz (2018) [51]	Turkey	Case–control	MRI	Hashemi	ACL injury	86	109	
Kizilgoz (2019) [52]	Turkey	Cohort	LR	Longitudinal (lines)	ACL injury	92	101	
Korthaus (2021) [53]	Germany	Case–control	MRI	Hudek	ACL injury	116	116	
Kumar Panigrahi (2020) [54]	India	Case–control	MRI	Hudek	ACL injury	100	100	
Lee (2018) [55]	Korea	Case–control	MRI	Longitudinal (lines)	ACLR graft failure	64	64	59.7
Levins (2016) [19]	USA	Case–control	MRI	Other	ACLR graft failure	11	44	41.6
Li (2014) [56]	China	Case–control	MRI	Hudek	ACLR graft failure	20	20	27.5
Li (2020) [57]	China	Case–control	LR	Longitudinal (circles)	ACL injury	32	32	
Milani (2022) [58]	Iran	Case–control	MRI	Hashemi	ACL injury	60	60	
Misir (2022) [18]	Turkey	Case–control	MRI	Hashemi	ACL injury + ACLR graft failure	352/91[b]	350/182[b]	60
Mukherjee (2017) [59]	India	Case–control	MRI	Hudek	ACL injury	27	28	
Ni (2020) [60]	China	Case–control	LR	Longitudinal (lines)	ACLR graft failure	25	50	25.4
Rahnemai-Azar (2016) [61]	USA	Case–control	MRI	Hudek	ACL injury	45	45	
Raja (2019) [62]	India	Case–control	MRI	Hashemi	ACL injury	55	55	
Ristic (2014) [63]	Serbia	Case–control	MRI	Hudek	ACL injury	30	30	
Sauer (2018) [4]	Denmark, New Zealand	Cohort	MRI	Hudek	ACLR graft failure	54	54	48[a]

(continued on next page)

Table 1 (*continued*)

Author (Year)	Country	Study design	Imaging modality	Measurement method for posterior tibial slope	Injury assessed	Number of knees included		Mean follow-up period for successful ACLR group (months)
						Injury group	Control group	
Sayit (2015) [64]	Turkey		MRI	Hudek	ACL injury	60	60	
Shelbourne (2021) [65]	USA	Cohort	LR	Hohmann (posterior tibial cortex)	ACLR graft failure	126	2228	139.2
Shen (2018) [66]	China	Case–control	MRI	Hudek	ACL injury	125	125	
Shen (2019) [67]	China	Case–control	MRI	Hudek	ACL injury	50	50	
Shi (2024) [68]	China	Case–control	LR	Longitudinal (lines)	ACLR graft failure	52	52	48[a]
Simon (2010) [69]	USA	Case–control	MRI	Hashemi	ACL injury	27	27	
Sonnery-Cottet (2011) [16]	France	Case–control	LR	Lateral mechanical axis	ACL injury	50	50	
Stijak (2007) [70]	Serbia, Switzerland	Case–control	MRI	Other	ACL injury	33	33	
Sturnick (2014) [26]	USA	Case–control	MRI	Other	ACL injury	88	88	
Su (2018) [15]	USA	Case–control	LR	Longitudinal (lines)	ACL injury + ACLR graft failure	77/46[b]	83/77[b]	NS
Sundar (2016) [71]	India	Case–control	MRI	Hashemi	ACL injury	199	290	
Suprasanna (2017) [72]	India	Case–control	MRI	Hashemi	ACL injury	33	33	
Tang (2024) [73]	China	Case–control	MRI	Hudek	ACL injury	56	70	
Teixeira Goncalves Alves (2022) [5]	Portugal	Case–control	MRI	Hudek	ACL injury	95	95	
Tensho (2023) [74]	Japan	Cross-sectional	LR	Longitudinal (lines)	ACL injury	187	187	
Terauchi (2011) [75]	Japan	Cross-sectional	MRI	Other	ACL injury	73	68	
Todd (2010) [76]	USA	Case–control	LR	Longitudinal (lines)	ACL injury	140	179	
Unal (2020) [77]	Turkey	Case–control	MRI	Other	ACL injury	63	63	
Van Diek (2013) [78]	USA, Netherlands	Case–control	MRI	Hashemi	ACL injury	45	43	
Vasta (2018) [79]	Italy, Portugal	Case–control	LR	Longitudinal (lines)	ACL injury	200	200	
Waiwaiole (2016) [80]	USA	Cross-sectional	MRI	Hudek	ACL injury	109	105	
Webb (2013) [81]	Australia	Case–control	LR	Longitudinal (lines)	ACLR graft failure	50	131	NS
Winkler (2021) [82]	USA, Germany	Cohort	LR	Longitudinal (lines)	ACLR graft failure	44	58	29[c]
Yaka (2022) [83]	Turkey	Case–control	LR	Longitudinal (lines)	ACL injury	32	40	
Ye (2022) [84]	China	Case–control	MRI	Hudek	ACLR graft failure	28	56	43.7
Zeng (2014) [85]	China	Case–control	LR	Longitudinal (lines)	ACL injury	73	73	
Ziegler (2020) [86]	USA	Cross-sectional	LR + MRI	Longitudinal (lines) + Hashemi	ACLR graft failure	90	109	15

USA = United States of America, LR = lateral radiograph, MRI = magnetic resonance imaging, ACL = anterior cruciate ligament, ACLR = anterior cruciate ligament reconstruction, NS = not stated.

[a] Minimum follow-up period (months) given instead as mean follow-up period not stated in text.

[b] Where a study investigates ACL injury and ACLR graft failure, the results are shown as ACL injury/ACLR graft failure.

[c] Median used instead of mean.

Posterior tibial slope and ACL injury – radiographic studies

Of the 53 studies analysing ACL injury, fifteen assessed PTS on lateral radiograph. With regard to measurement technique, the longitudinal axis was the most common reference point for PTS, with eleven studies using the longitudinal axis determined by the circle method [23], and two studies using the longitudinal axis determined by the midpoint method [22]. In addition, one study used the posterior tibial cortex as the reference point for PTS [42], and one study used the lateral mechanical axis of the leg [16].

Of the fifteen radiographic studies assessing PTS, twelve studies found that increased PTS was associated with an increased risk of ACL injury. However, three studies failed to detect a statistically significant difference in PTS between the ACL injury group and the ACL intact control group. The pooled treatment effect is shown by the forest plot (Fig. 3).

Posterior tibial slope and ACLR graft failure – radiographic studies

Of the 24 total studies analysing ACLR graft failure, thirteen measured PTS using lateral radiographs. Eleven of these studies specified medial PTS, with one also measuring lateral PTS [2]. Two studies did not explicitly specify between medial and lateral tibial plateaus but were presumed to be medial based on their measurement methods, and were pooled with studies measuring medial PTS for analysis [84]. Many different measurement techniques were used for PTS measured on lateral radiographs. Eleven studies measured the PTS against the longitudinal axis of the tibia, with nine studies using lines, and two studies using circles. Two studies used the posterior tibial cortex.

Ten of thirteen studies found that increased medial PTS was associated with an increased risk of ACLR reinjury, with three studies failing to detect a statistically significant difference. A meta-analysis was performed on values for medial PTS, and the pooled treatment effect is shown by the

Table 2
Pooled results for meta-analysis examining difference between anterior cruciate ligament injury group versus intact native anterior cruciate ligament control group.

Measurement	Mean difference (95% CI)	p-value
PTS (LR)	1.637 (1.075, 2.198)	p < 0.001
LPTS	1.687 (1.326, 2.047)	p < 0.001
MPTS	0.966 (0.554, 1.378)	p < 0.001
LMS	3.253 (1.698, 4.808)	p < 0.001
MMS	1.356 (−0.018, 2.730)	p = 0.053
LMBA	−3.847 (−6.377, −1.317)	p = 0.003
MMBA	−2.767 (−5.873, 0.339)	p = 0.081

PTS = posterior tibial slope, LPTS = lateral posterior tibial slope, MPTS = medial posterior tibial slope, LMS = lateral meniscal slope, MMS = medial meniscal slope, LMBA = lateral meniscal bone angle, MMBA = medial meniscal bone angle, LR = lateral radiograph, CI = confidence interval.

forest plot (Fig. 4). Additionally, the single study assessing lateral PTS independently showed that patients experiencing ACLR reinjury had greater lateral PTS values than the successful ACLR group [36].

Posterior tibial slope and ACL injury – MRI studies

Of the 38 studies analysing ACL injury that were measured using MRI, 33 described both medial PTS and lateral PTS, four described lateral PTS only, and one described medial PTS only [75]. The measurement techniques described by Hudek et al. and Hashemi et al. were the most commonly used for assessing PTS on MRI, with eighteen and thirteen studies employing these techniques, respectively [25,24]. Additionally, seven studies reported using various other methods.

Of the 37 total studies assessing lateral PTS, 27 studies found that increased lateral PTS was associated with an increased risk of ACL injury, with ten studies failing to detect a statistically significant difference

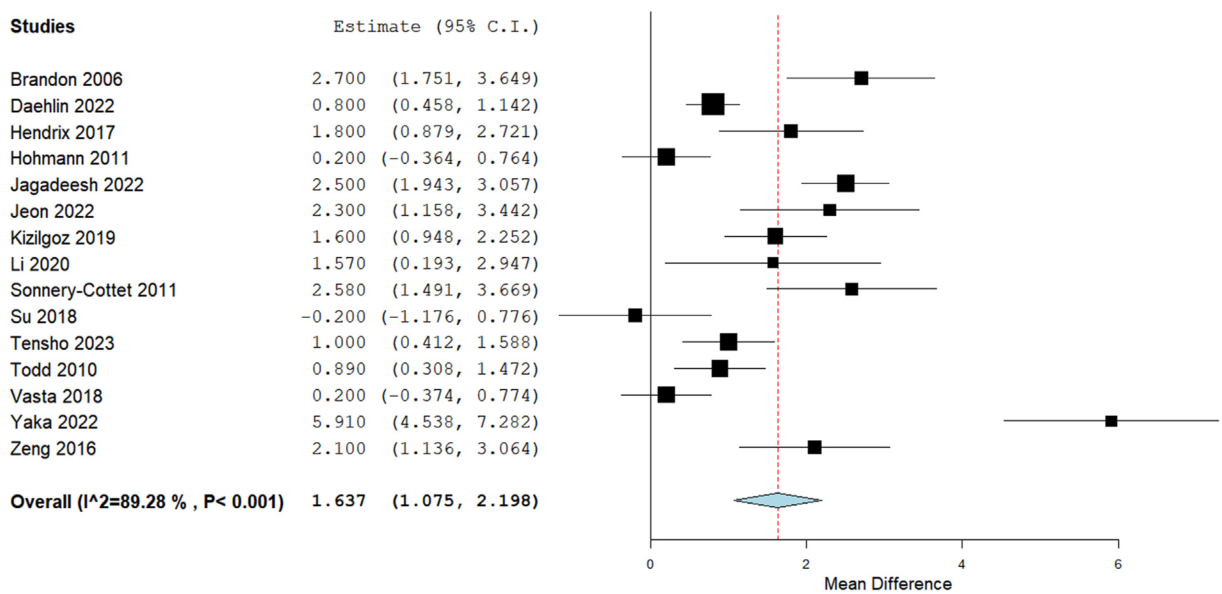

Fig. 3. Meta-analysis of radiographic studies evaluating posterior tibial slope in the ACL injury group versus intact native ACL control group. CI = confidence interval, ACL = anterior cruciate ligament.

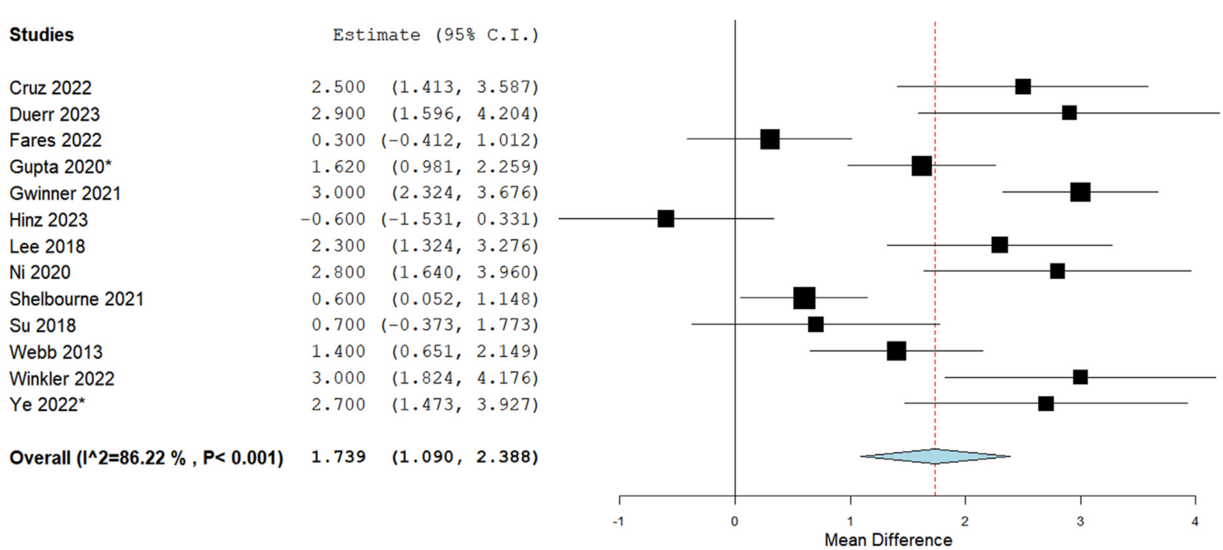

Fig. 4. Meta-analysis of radiographic studies evaluating medial posterior tibial slope in the ACLR graft failure group versus successful ACLR control group. *did not explicitly specify medial or lateral posterior tibial slope. CI = confidence interval, ACLR = anterior cruciate ligament reconstruction.

between the injury and control group. The pooled treatment effect is shown by the forest plot (Fig. 5).

From the 34 total studies assessing medial PTS, nineteen studies failed to detect a statistically significant difference between the two groups, with thirteen studies finding that increased medial PTS was associated with an increased risk of ACL injury. Two studies suggested that decreased medial PTS was associated with increased risk of ACL injury. The pooled treatment effect is shown by the forest plot (Fig. 6).

Posterior tibial slope and ACLR graft failure – MRI studies

Thirteen included studies assessed the impact of posterior tibial slope on ACLR reinjury using MRI. Thirteen MRI studies measured lateral PTS, with ten also assessing medial PTS. Six studies employed Hudek's method, five used Hashemi's method, and two studies utilized alternative measurement techniques.

Of the thirteen studies included in the analysis of lateral PTS, eight studies found that increased lateral PTS was associated with ACLR graft failure, with five studies failing to find a statistically significant difference. The pooled treatment effect is shown by the forest plot (Fig. 7).

Of the eleven studies measuring medial PTS, six studies demonstrated a statistically significant increase in medial PTS for the ACLR graft failure group compared to the control group, with five studies failing to find a statistically significant difference. The pooled treatment effect is shown by the forest plot (Fig. 8).

Meniscal slope and ACL injury – MRI studies

Six studies analysing ACL injury measured the meniscal slope using MRI. Five studies described both medial and lateral MS and one study described lateral MS only [53].

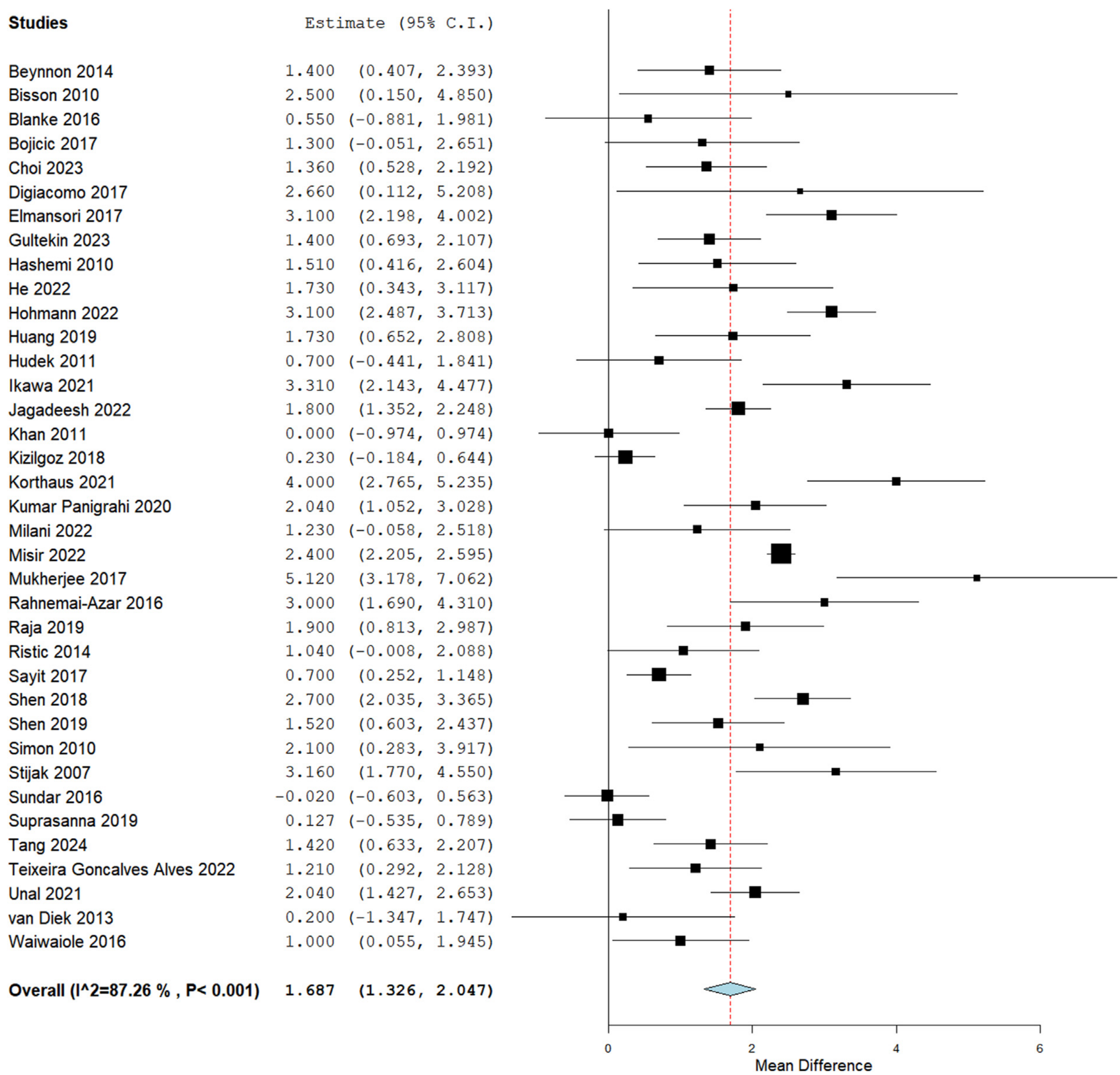

Fig. 5. Meta-analysis of MRI studies evaluating lateral posterior tibial slope in the ACL injury group versus intact native ACL control group. CI = confidence interval, MRI = magnetic resonance imaging, ACL = anterior cruciate ligament.

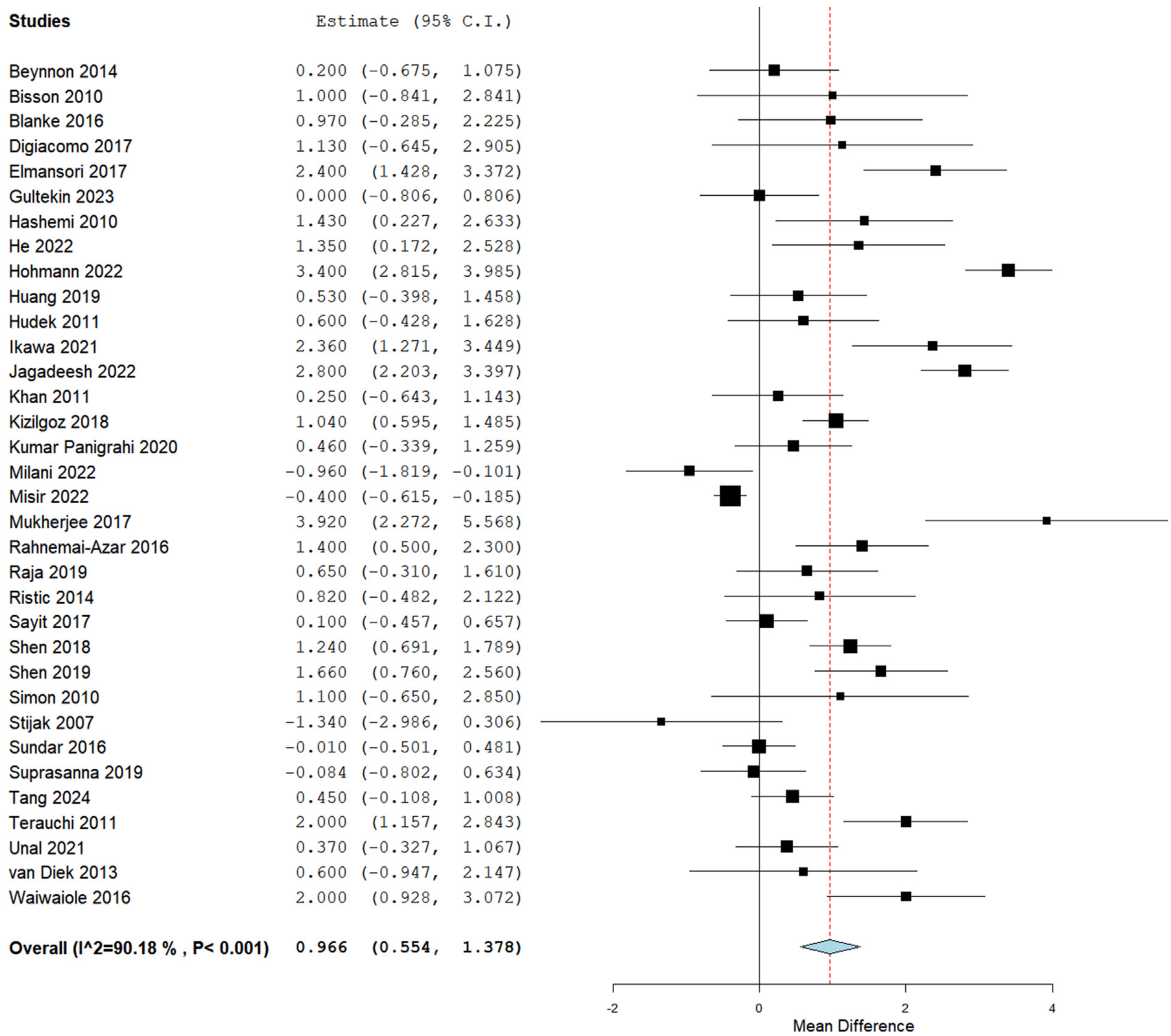

Fig. 6. Meta-analysis of MRI studies evaluating medial posterior tibial slope in the ACL injury group versus intact native ACL control group. CI = confidence interval, MRI = magnetic resonance imaging, ACL = anterior cruciate ligament.

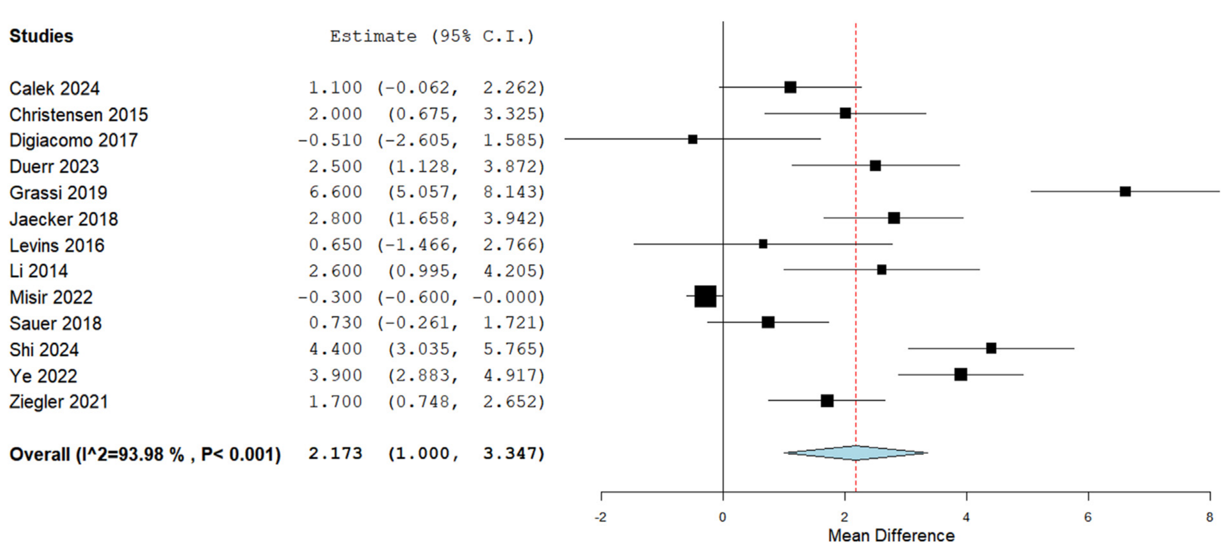

Fig. 7. Meta-analysis of MRI studies evaluating lateral posterior tibial slope in the ACLR graft failure group versus successful ACLR control group. CI = confidence interval, MRI = magnetic resonance imaging, ACLR = anterior cruciate ligament reconstruction.

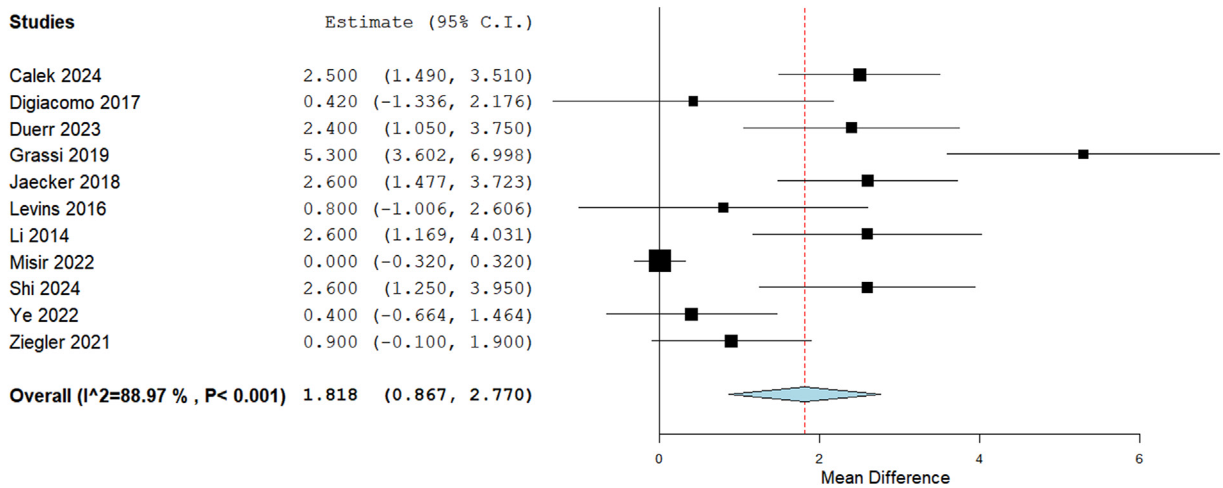

Fig. 8. Meta-analysis of MRI studies evaluating medial posterior tibial slope in the ACLR graft failure group versus successful ACLR control group. CI = confidence interval, MRI = magnetic resonance imaging, ACLR = anterior cruciate ligament reconstruction.

Five studies found that increased lateral MS was associated with an increased risk of ACL injury, while one study failed to detect a statistically significant difference [73]. The pooled treatment effect is shown by the forest plot (Fig. 9).

Of the four total studies assessing medial MS, three studies found that increased medial MS was associated with an increased risk of ACL injury, and two studies failed to detect a statistically significant difference between the injury and control group.

Meniscal slope and ACLR graft failure – MRI studies

Two studies reported the effect of both the medial and lateral meniscal slopes on ACL graft failure [18,31]. When pooled, no statistically significant difference was found (Table 3).

Meniscal bone angle and ACL injury – MRI studies

Six studies evaluated the relevance of meniscal bone angle on ACL injury. All six of these studies measured MBA using MRI. Four studies described both medial and lateral MBA and two studies described lateral MBA only. The measurement technique described by Sturnick et al. was the most popular amongst the six included studies, with four studies using it to measure MBA [26].

Of the six total studies assessing lateral MBA, five studies found that decreased lateral MBA was associated with an increased risk of ACL injury, with one study failing to detect a statistically significant difference between the injury and control group [30]. The pooled treatment effect is shown by the forest plot (Fig. 10).

Of the four total studies assessing medial MBA, two studies found that decreased medial MBA was associated with an increased risk of ACL injury, one study suggested that increased medial MBA was associated with increased risk of ACL injury [18], and one study failed to detect a statistically significant difference between the injury and control group [87].

Meniscal bone angle and ACLR graft failure – MRI studies

Three studies assessing ACLR graft failure risk measured lateral MBA, with two studies also measuring the medial MBA. All studies used the measurement technique as described by Sturnick [87].

Pooled data failed to identify a statistically significant difference between groups for either lateral or medial MBA (Table 3). No studies were able to identify a statistically significant difference for lateral or medial MBA in individual analysis (Table 3).

DISCUSSION

The key findings of this systematic review were that increased PTS significantly increases the risk of ACL injury and the risk of ACLR reinjury. Increased lateral MS and decreased lateral MBA were also significantly associated with a higher risk of ACL injury, but a statistically significant relationship was not established in the case of ACLR reinjury. Ultimately, the initial hypothesis positing a uniform increase in ACL injury and graft failure risk with greater PTS is supported. However, the hypothesis of increased MS and decreased MBA is supported only in the lateral compartment for ACL injury, with meniscal measurements not having established a statistically significant relationship with ACLR graft failure, and the medial meniscal measurements not significantly linked to either ACL injury or ACLR graft failure risk.

The analysis comparing ACL injury to an intact ACL control group includes 53 studies analysing a total of 10,411 knees. Mean PTS values obtained through lateral radiograph in the control group ranged from 3.4° to 9.4°, while the ACL-injured group exhibited higher PTS values with a range of 5.4° to 14.2°, with the mean difference being 1.64° (Table 2 and Fig. 11). This trend was consistent through comparison of the lateral PTS and medial PTS on MRI, with both differences being statistically significant. Almost one-third of the studies (24 of 75) were rated as having a medium risk of bias based on MINORS, primarily due to the predominance of Level IV studies. Nonetheless, the large number of overall included studies provides valuable insights. Prospective assessment of this outcome remains challenging, as imaging is typically performed only after ACL rupture.

The analysis comparing ACLR reinjury to a successful ACLR control group incorporates 24 studies encompassing 5,412 knees. Mean PTS values measured via lateral radiograph in the control group ranged from 4.8° to 14.4°, whereas the ACLR reinjured group had higher PTS values, ranging from 5.5° to 17.2°, with a mean difference of 1.76° (Fig. 12). This trend was also evident in comparisons of lateral PTS and medial PTS on MRI, with both differences statistically significant.

When comparing ACL injury and ACLR reinjury groups to their respective control groups, a more substantial mean difference was observed for lateral PTS in contrast to medial PTS, which may indicate a greater impact of lateral slope in ACL injury. Biomechanically, this may be explained by the mechanism proposed by Simon and colleagues [69]. Under an axial load, a steeper lateral slope will cause the lateral femoral condyle to slide posteriorly down the lateral tibial plateau, using the medial tibial plateau as a pivot point. This movement results in increased relative tibial internal rotation, which has been shown to cause additional strain on the ACL and lateral meniscus [88,89]. Differences between the lateral PTS and medial PTS have been shown to influence

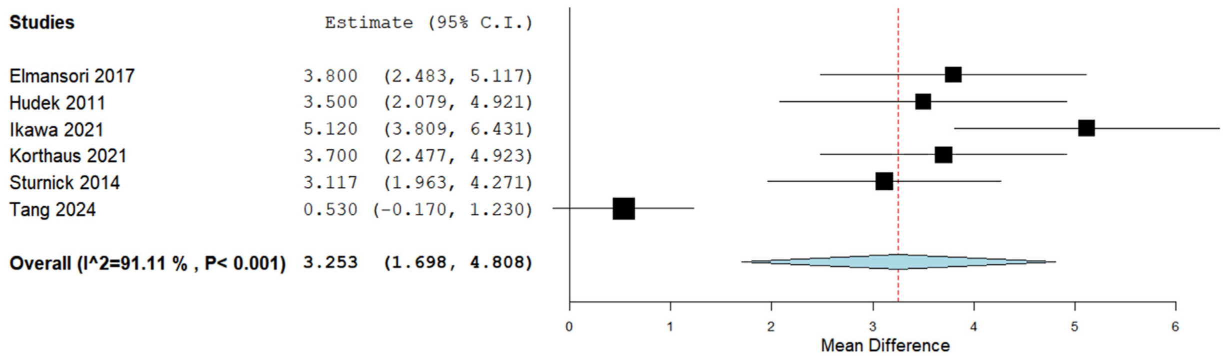

Fig. 9. Meta-analysis of MRI studies evaluating lateral meniscal slope in the ACL injury group versus intact native ACL control group. CI = confidence interval, MRI = magnetic resonance imaging, ACL = anterior cruciate ligament.

Table 3
Pooled results for meta-analysis examining difference between anterior cruciate ligament reconstruction graft failure group versus successful anterior cruciate ligament reconstruction control group.

Measurement	Mean difference (95% CI)	p-value
PTS (LR)	1.739 (1.090, 2.388)	$p < 0.001$
LPTS	2.173 (1.000, 3.347)	$p < 0.001$
MPTS	1.818 (0.876, 2.770)	$p < 0.001$
LMS	0.000 (−0.898, 0.899)	$p = 1.000$
MMS	1.162 (−0.692, 3.016)	$p = 0.219$
LMBA	−1.521 (−3.951, 0.910)	$p = 0.220$
MMBA	0.196 (−0.070, 0.463)	$p = 0.148$

PTS = posterior tibial slope, LPTS = lateral posterior tibial slope, MPTS = medial posterior tibial slope, LMS = lateral meniscal slope, MMS = medial meniscal slope, LMBA = lateral meniscal bone angle, MMBA = medial meniscal bone angle, LR = lateral radiograph, CI = confidence interval.

tibiofemoral rotation [89], and should thus be considered separately as risk factors of ACL injury [47]. A similar trend was observed for MS and MBA, where discrepancies are more pronounced on the lateral side compared to the medial side.

As a risk factor for failure after ACLR, PTS is modifiable by osteotomy [1,11,12,90]. However, slope-reducing osteotomy is a major intervention that carries an increased risk of complications, extends operative time, and requires a longer post-operative rehabilitation period [91]. The use of slope-reducing osteotomy was first reported in second- and third-revision settings [10,11]; however, given the importance of tibial slope as a risk factor for reconstruction failure, several authors have now published on slope-reducing osteotomy at first revision [1,12]. Exceptionally, some authors have proposed its application in ACLR settings where PTS values are ≥12° [92].

Prior case–control studies indicate that the risk of ACLR reinjury increases significantly, by 5 to 11.6 times, when the PTS is ≥ 12° as measured on lateral radiograph [40,81,93]. As such, a PTS ≥12° is an increasingly accepted indication for adjunct procedures such as slope-reducing osteotomy, with the goal of decreasing the PTS to <6° [9] when considering clinical and biomechanical data together. Using rerupture rates reported by Webb et al. (59% incidence of graft rupture in patients with PTS >12° versus 9% incidence in patients with PTS ≤6°) [81], the number needed to treat (NNT) with slope-reducing osteotomy to prevent one patient from ACL graft rupture would be 2.0. Comparatively, the STABILITY Study found that the NNT with lateral extra-articular tenodesis (LET) to prevent one ACL graft rupture was 14.3 over the first two postoperative years [94]. Given these numbers, it is likely that slope-reducing osteotomy will be explored further in coming years. Although long-term clinical studies on slope-reducing osteotomy remain limited, early findings suggest promising outcomes for knee stability, higher rates of return to sport, and decreased graft failure [1,11,90].

LET has previously been indicated regardless of PTS in a revision ACLR setting [95]. Biomechanical studies have consistently shown that insufficient anterolateral structures lead to increased anterior knee translation, pivot shift, and internal rotation, resulting in considerable anterior knee laxity [96]. Additionally, increasing PTS correlates with a linear rise in graft force across all flexion angles and further exacerbates anterior tibial translation [8,97]. A biomechanical analysis by Pearce and his colleagues demonstrated that combining LET with ACLR reduces graft forces at 30° of flexion by 8.3% and decreases anterior tibial translation during extension compared to ACLR alone [98]. Therefore, the inclusion of LET in ACLR cases with high PTS would seem appropriate.

The relationship between PTS and ACL injury may not extend to skeletally immature patients. Farid et al. analysed ten studies in paediatric and adolescent patients, finding that lateral PTS (LPTS) approached but did not reach statistical significance as a risk factor for ACL injury ($p < 0.1$). This suggests that, unlike in adults, increased PTS may not be a key risk factor, despite plausible biomechanical reasoning. The authors further highlight that high heterogeneity ($I^2 = 84$ %), mainly attributed to measurement methods, suggests inconsistencies and propose further

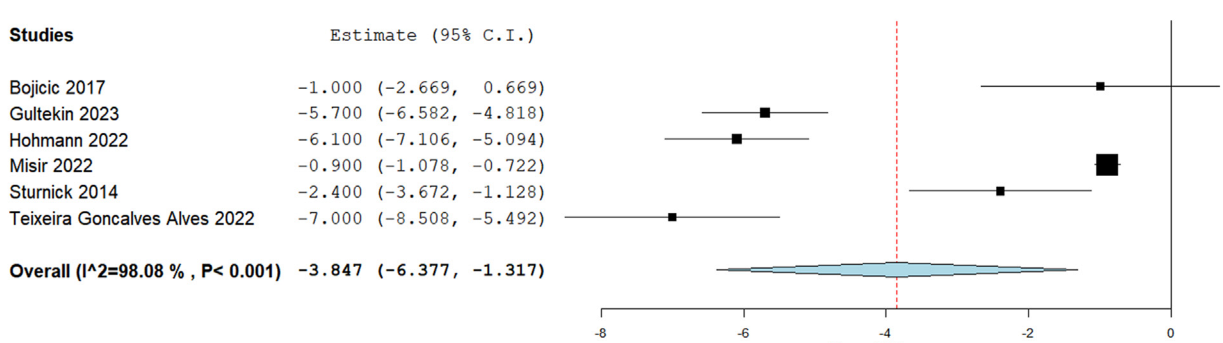

Fig. 10. Meta-analysis of MRI studies evaluating lateral meniscal bone angle in the ACL injury group versus intact native ACL control group. CI = confidence interval, MRI = magnetic resonance imaging, ACL = anterior cruciate ligament.

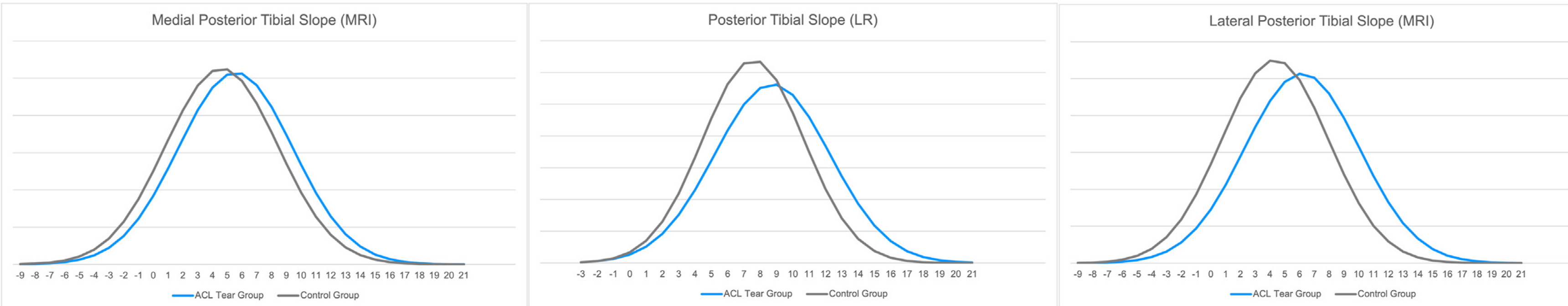

Fig. 11. Normal distribution of posterior tibial slope (LR), lateral posterior tibial slope (MRI), and medial posterior tibial slope (MRI) for both ACL injury and intact ACL control groups. The analysis suggests an "at-risk" threshold starting at 10.7° when posterior tibial slope is measured on LR, marking the point where risk seems to increase significantly. ACL = anterior cruciate ligament; LR = lateral radiograph; MRI = magnetic resonance imaging.

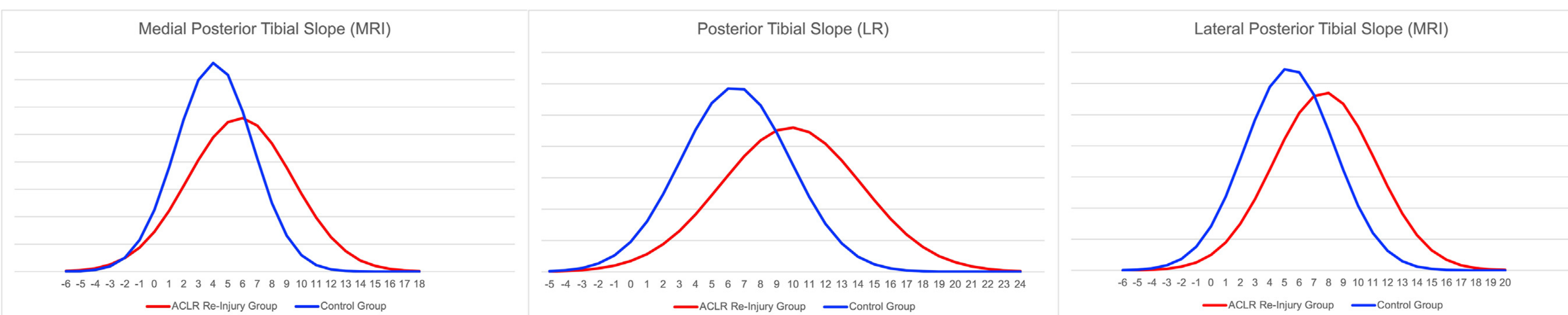

Fig. 12. Normal distribution of posterior tibial slope (LR), lateral posterior tibial slope (MRI), and medial posterior tibial slope (MRI) for both ACL reconstruction failure and successful ACL reconstruction control groups. ACL = anterior cruciate ligament; LR = lateral radiograph; MRI = magnetic resonance imaging.

research to clarify the role of PTS in ACL injury risk in this population [99].

MS and MBA have only recently been suggested as potential modifiers for ACL injury and re-injury. The values for MS are typically smaller than PTS, indicating that the meniscus tends to decrease the observable slope and correct it towards horizontal [3]. It is suggested that the meniscal slope may actually represent the functional slope, though this remains unproven [25]. Acting as a wedge between the posterior femoral condyle and the posterior tibial plateau, the posterior meniscal horn mitigates posterior displacement, potentially counteracting the posterior inclination of the PTS [100]. Although the role of the meniscus in altering the functional slope remains unproven, its loss may increase anterior tibial translation (medial meniscus) and rotation (lateral meniscus) [13], increasing the risk of ACL injury. The observation of a greater lateral MS in cases of ACL injury suggests that a higher MS correlates with an increased risk of ACL injury.

MBA is another value that measures the contribution of the meniscus to the functional slope [4,5], with some authors proposing that lateral PTS to MBA ratio is a predictive variable for ACL injury [5,101]. Reducing the MBA allows the lateral femoral condyle to more easily roll over the posterior horn of the lateral meniscus, especially with a steep PTS, generating momentum. Consequently, avoiding meniscectomy or opting for meniscal repair in cases of concurrent ACL injury may be advisable.

In the case of ACLR reinjury risk, this review found only two relevant articles reporting MS values [18,31] and three reporting the association of MBA values [4,18,19], with no prior systematic reviews to our knowledge reporting this. Due to the limited number of studies, there is insufficient evidence to show that MS or MBA significantly impacts ACLR reinjury risk and should impact management at this stage.

Limitations and future directions

The high variability in study methodologies and reporting standards introduces heterogeneity. To mitigate this, a random-effects model was applied, and sensitivity analyses were conducted. However, concerns persist regarding data comparability and the reliability of pooled results. Moreover, the limited number of studies addressing MS and MBA measurements influenced its impact on the analysis. Future research should focus on evaluating the clinical indications and outcomes of slope-reducing osteotomy in this context, as well as further establishing the relationship between MS and MBA measurements and the risk of ACL injury and ACLR graft failure.

CONCLUSION

This systematic review highlights the association between increased PTS with a heightened risk of ACL injury and ACLR graft failure in both the medial and lateral compartments, regardless of the imaging method employed. Additionally, the strong association between increased lateral MS and decreased lateral MBA in ACL injury risk highlights the importance of preserving the meniscus when possible.

Article summary

This systematic review highlights the significant association of increased PTS as a risk factor for primary ACL injury and graft failure after ACL reconstruction. This paper also explores the role of meniscal slope in ACL injury and re-injury.

Authorship contributions

All authors read and approved the final manuscript.

CZ: methodology, data curation, formal data analysis, writing - original draft, writing - review and editing.

FMB: methodology, data curation, formal data analysis, writing - original draft.

TL: conceptualisation, formal analysis, supervision, writing - review and editing.

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Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.jisako.2025.100854.

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