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SYSTEMATIC REVIEW

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Combining tibial tubercle osteotomy with medial patellofemoral ligament reconstruction often yields better outcomes in treating patellofemoral instability: a systematic review and meta-analysis of case-control studies

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Abstract

Purpose Tibial tubercle osteotomy (TTO) is often employed for certain patellofemoral instability (PFI) cases, though its indications and effectiveness are not widely accepted. This systematic review gathers recent studies comparing isolated medial patellofemoral ligament reconstruction (iMPFLR) to MPFLR combined with TTO in managing PFI and to offer recommendations for clinicians when selecting TTO. This review proposes that MPFLR combined with TTO is superior to iMPFLR and that the combined procedure does not increase the incidence of postoperative complications.

Methods Following the Preferred Reporting Items for Systematic Reviews and Meta-Analyses 2020 (PRISMA 2020), extensive searches were performed on August 20, 2024, across PubMed/Medline, Embase, and Cochrane databases to locate relevant studies. Data on research protocols, participant characteristics (including epidemiological and radiographic features), functional scores, and complications were collected and examined. A meta-analysis was conducted to compare the outcomes between the two surgical techniques.

Results This systematic review analyzed 10 studies involving 715 participants, divided into a control group (which underwent iMPFLR) and an experimental group (which underwent MPFLR combined with TTO). In the control group, the incidence of severe trochlear dysplasia before surgery was 68.3% (95% CI [67.3-69.3%]), and the mean preoperative tibial tubercle to trochlear groove distance (TT-TG) was 16.1 mm (95% CI [15.8–16.3]). In the experimental group, both were respectively 79.1% (95% CI [77.5–80.7]) and 20.2 mm (95% CI [20.0-20.4]). Eight studies (80%) reported postoperative Kujala scores, with an average score of 85.1 (95% CI [84.4–85.9]) for the control

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group and 85.4 (95% CI [84.9–85.9]) for the experimental group (I^2=22.7%). Four studies (40%) reported postoperative Lysholm scores, with an average score of 89.4 (95% CI [88.9–89.9]) for the control group and 89.1 (95% CI [89.0-89.3]) for the experimental group (I^2=0%). The mean surgical failure rate for the control group was 5.1% (95% CI [4.7-5.6%]), compared to 3.2% (95% CI [3.0-3.4%]) for the experimental group, with an odds ratio (OR) of 2.18 (95% CI [1.05–4.53], I^2=0%, p=0.738). The rate of secondary surgeries in the control group was 1.9% (95% CI [1.6–2.2]), while in the experimental group it was 10.7% (95% CI [9.4–12.1]), with an OR of 0.12 (95% CI [0.03–0.54], I^2=63.1%, p=0.028).

Conclusion The combination of MPFLR and TTO for treating PFI yields knee joint function comparable to that achieved with MPFLR alone. The approach does not elevate the failure rate of the surgery or the incidence of other adverse events. However, the combined approach may prolong the postoperative rehabilitation process and typically requires removal of internal fixation devices, resulting in a higher rate of secondary surgeries.

Keywords Patellofemoral instability, Medial patellofemoral ligament, Tibial tubercle osteotomy, Treatment, Meta-analysis

Introduction

Patellofemoral instability (PFI) is a common condition in adolescent knee pathology [1]. The incidence of initial patellar dislocation (PD) is approximately 5.8/100,000 individuals, increasing to 29/100,000 among those aged 10–17 years [2–4]. Without timely and appropriate surgical intervention, over one-third of these cases may progress to secondary recurrent patellar dislocation (RPD) [1, 5, 6]. Approximately 94% of initial PD cases involve damage to the medial patellofemoral ligament, making medial patellofemoral ligament reconstruction (MPFLR) a widely used surgical treatment for PFI [7–9]. Nevertheless, MPFLR only restores the tension of the medial soft tissue of the patella, and studies suggest that the incidence of complications post-surgery can be as high as 25% [8], particularly in patients with bony structural abnormalities, where reliance solely on soft tissue procedures often fails to yield optimal results.

Tibial tuberosity osteotomy (TTO) enhances knee extension mechanism alignment by adjusting the tibial tuberosity's position, thus altering forces on the patellofemoral joint [10]. It is considered effective for patients with an increased tibial tubercle to trochlear groove distance (TT-TG) or abnormal patellar positioning. However, the TT-TG distance is affected by factors like trochlear shape, distal femur rotation, and tibial axial alignment [1, 7, 11–14], making the indications for TTO are complex and multidimensional. TTO, involving osteotomy and fixation, is more invasive than soft tissue surgery and is perceived to have a higher complication rate. Currently, international long-term follow-up studies on TTO outcomes are limited, leaving its optimal indications and prognosis in a "gray area" that warrants further investigation.

This systematic review collates recent international studies comparing isolated MPFLR (iMPFLR) and MPFLR combined with TTO in treating PFI. It reviews imaging data, functional scores, and postoperative complications between the two groups, aiming to affirm the efficacy of TTO and provide clinical recommendations on the selection of TTO. The hypothesis of this review is that MPFLR combined with TTO is more effective than iMPFLR in treating PFI, without increasing the incidence and severity of complications.

Methods

This study was conducted in accordance with the Preferred Reporting Items for Systematic Reviews and Meta-Analyses 2020 (PRISMA 2020) guidelines, which established the foundation for this systematic review.

Search Strategy

The search keywords identified were: medial patellofemoral ligament, MPFL, reconstruction, MPFLR, tibial tubercle, osteotomy, transfer, TTO, TTT. Synonyms for these keywords were expanded, and search precision was limited through specific combinations. The search formula was determined by arranging and combining the keywords, as detailed in Table 1.

Literature screening

Inclusion criteria included: (1) Participants diagnosed with PFI (including patellar dislocation and high-riding patella) and a preoperative TT-TG≥15 mm; (2) Populations undergoing either iMPFLR or MPFLR+TTO assessed for prognosis; (3) Average follow-up duration of ≥1 year in all studies; (4) Studies ranked as level I ~ III evidence by the Oxford Centre for Evidence-based Medicine; (5) Studies with reasonable design, complete required data, and clear outcome effects. Exclusion criteria included: (1) Studies without full text available in English; (2) Data derived from non-human studies; (3) Document types such as autobiographies, interviews, clinical protocols, case reports, case series, reviews, systematic reviews, technical papers, conference abstracts, reports of congenital anomalies, author replies, letters, expert opinions. The inclusion and exclusion criteria are detailed in Table 2.

Table 1 Search strategy

1	exp medial patellofemoral ligament/ or exp MPFL/
2	medial patellofemoral ligament reconstruction.mp or MPFLR.mp
3	1 or 2
4	exp tibia/ or exp tibial/
5	exp tubercle/ or exp tuberosity/
6	exp osteotomy/ or exp transfer/
7	(and/4–6) or exp TTO/ or exp TTT/
8	exp prognosis/
9	(3 and 7) or (7 and 8)

Note The position of "exp" in the search formulas of different databases is not completely the same, but all indicate expanded search; "mp" indicates maximum precision search. The exclusion criteria have been limited through the filtering systems of each database during search process

Table 2 Inclusion and exclusion criteria in this study

Inclusion criteria	Exclusion criteria
Participants diagnosed with PFI and preoperative TT-TG ≥ 15 mm	Studies lacking full text or not available in English
Subjects receiving iMPFLR and MPFLR + TTO assessed for prognosis	Non-human research materials
Average follow-up time of each study is ≥ 1 year	Research materials in the form of autobiographies, interviews, clinical protocols, case reports, case series, reviews or systematic reviews, technical papers, conference abstracts, reports on congenital abnormalities, author review responses and letters, and expert opinions
Studies ranked as level I ~ IV evidence by the Oxford Centre for Evidence-based Medicine	
The research scheme is reasonable, the required data are complete, and outcome effect is clear	

Note PFI includes PD and patella alta; MPFLR + TTO includes medialization, anteromedialization and distalization

Initial Screening: On August 20, 2024, author Fang searched relevant studies in PubMed/Medline, Embase, and Cochrane databases using the formulated search strategy. Database filters were applied to adhere to the exclusion criteria; another author Zhao independently repeated the search process. Both reviewers conducted their screening independently and blindly, and the retrieved articles were compiled in Endnote 21 software to remove duplicates. Secondary Screening: Articles retained from the initial screening were re-evaluated by authors Wang and Ji who reviewed abstracts and reapplied the inclusion criteria to exclude non-qualifying studies. Final Selection: For articles retained after the secondary screening, author Ding reviewed the full texts for final selection, also resolving any discrepancies in article eligibility. Articles that met all criteria were were included.

Quality assessment

Risk of Bias Assessment: The Risk of Bias in Non-randomised Studies—of Interventions (ROBINS-I) tool was utilized by author Meng to assess the risk of bias across seven dimensions in the finally included studies.

Study Evaluation: The Methodological Index for Non-Randomized Studies (MINORS) criteria, specifically designed for non-randomized controlled trials, were employed by author Wang to evaluate the included studies.

Data extraction and analysis

Following the search, screening, and quality assessments, data were extracted from the qualified studies. This data included baseline information, surgical methods, and outcomes (pre- and post-operative imaging data, final follow-up knee function scores, and postoperative complications). Key evaluation metrics selected were average TT-TG, Caton-Deschamps Index (CDI), average Kujala score, Lysholm score, Tegner score, and the rates of postoperative failure and reoperation. Continuous variables were reported as mean ± standard deviation, and categorical variables as frequency or proportion. In Stata/MP 17.0, the weighted mean for each variable was calculated using the mean/ratio + weight command. Fixed/random effects meta-analysis was performed using Hedges's method and the metan command, and heterogeneity was assessed. The degree of heterogeneity was expressed using the odds ratio (OR) and I^2 statistic, with p-values and 95% CIs reported.

Results

Literature search

After the initial screening, a total of 210 articles were obtained: 185 from the PubMed/Medline database, 23 from Embase, and 2 from Cochrane. After a full-text review, 26 studies were excluded, including 16 that did not use TTO as an intervention for group comparison, 7 with primary outcome measures that did not meet the requirements, and 3 involving too many subjects undergoing other interfering procedures. Ultimately, 10 eligible studies were included. The screening process and results are illustrated in Fig. 1.

Study quality

Of the final 10 studies included, nine were retrospective and one was a prospective cohort study. The evidence levels were distributed as follows: one study at level II (10%), seven at level III (70%), and two at level IV (20%). The overall risk of bias, assessed using the ROBINS-I, indicated that eight studies had a "moderate risk" of bias and two had a "high risk". The overall risk of bias for each study is presented in Table 3. All studies assessed with the MINORS criteria were deemed "high quality". Notably, the study by Franciozi et al. disclosed funding from companies such as Smith & Nephew, DePuy, and Arthrex, while the remaining studies reported no conflicts of interest. The potential bias introduced by this funding is considered minimal in affecting the study

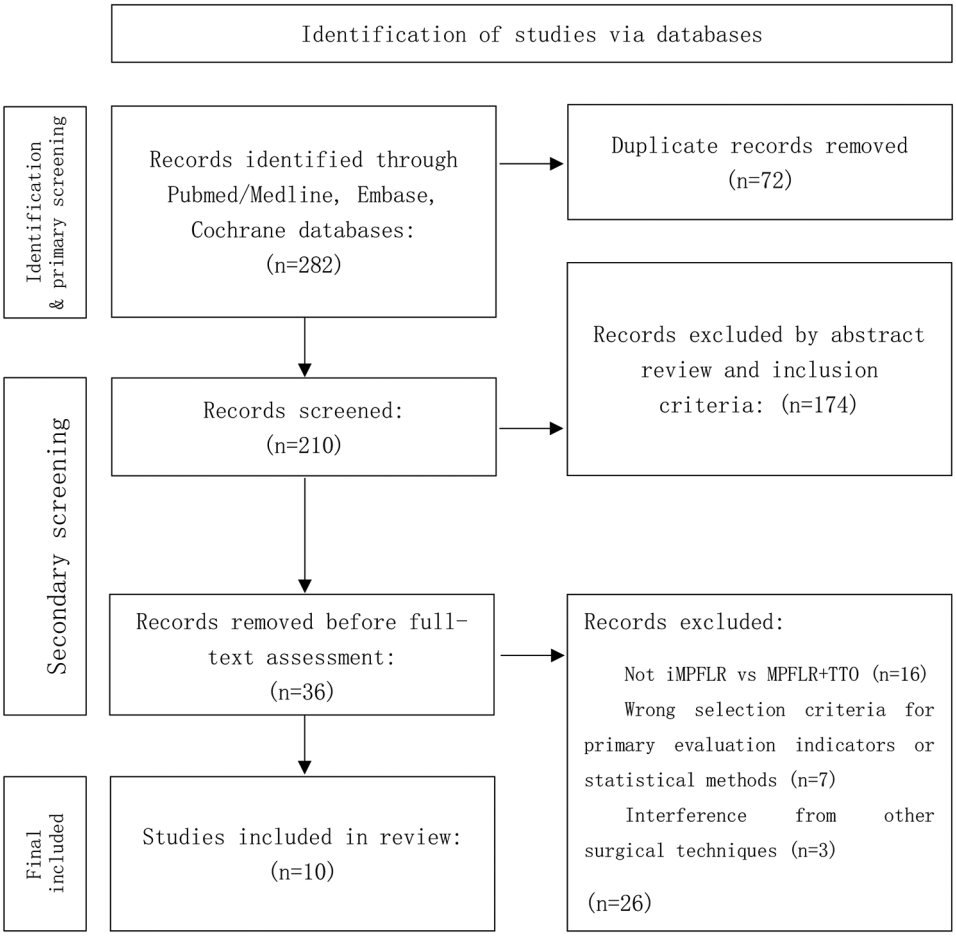

Fig. 1 PRISMA 2020 flow diagram depicting the screening process

Table 3 Individual risk assessment according to ROBINS-1 tool

Author	Bias due to confounding	Bias due to selection of participants	Bias in measurement classification of interventions	Bias due to deviations from intended interventions	Bias due to missing data	Bias in measurement of outcomes	Bias in selection of the reporter results
Pautasso, et al. [19]	Low	Low	Moderate	Low	Low	Moderate	Low
Hao, et al. [21]	Low	Low	Moderate	Low	Low	Moderate	Low
Kim, et al. [22]	Moderate	Low	Moderate	Moderate	Low	Moderate	Low
Perkins, et al. [24]	Low	Low	Moderate	Low	High	Moderate	Low
Franciozi, et al. [17]	Moderate	Moderate	High	Low	Low	Moderate	Moderate
Zhang, et al. [15]	Moderate	Moderate	Moderate	Moderate	Low	Moderate	Moderate
Markus, et al. [20]	Low	Moderate	Moderate	Low	Low	Moderate	Moderate
Hashimoto, et al. [18]	Low	Moderate	Moderate	Low	Moderate	Moderate	Low
Tscholl, et al. [32]	Low	Moderate	Moderate	Low	Low	Moderate	Low
Xu, et al. [23]	Low	Low	High	Moderate	Moderate	Moderate	Moderate

outcomes. This systematic review analyzes the prognostic differences between the iMPFLR and MPFLR+TTO groups, assessing the effects and influencing factors of TTO surgery. However, significant differences in the indications for surgery between the groups are noted in clinical practice. Clinicians typically recommend combined surgery for patients with a greater TT-TG distance, concurrent trochlear dysplasia, or patellofemoral osteoarthritis (PFOA). This disparity in indications poses a challenge in achieving a balanced baseline between the groups for comparison, leading to potential confounding factors in this review. To mitigate such biases, the preoperative characteristics of the patients were summarized.

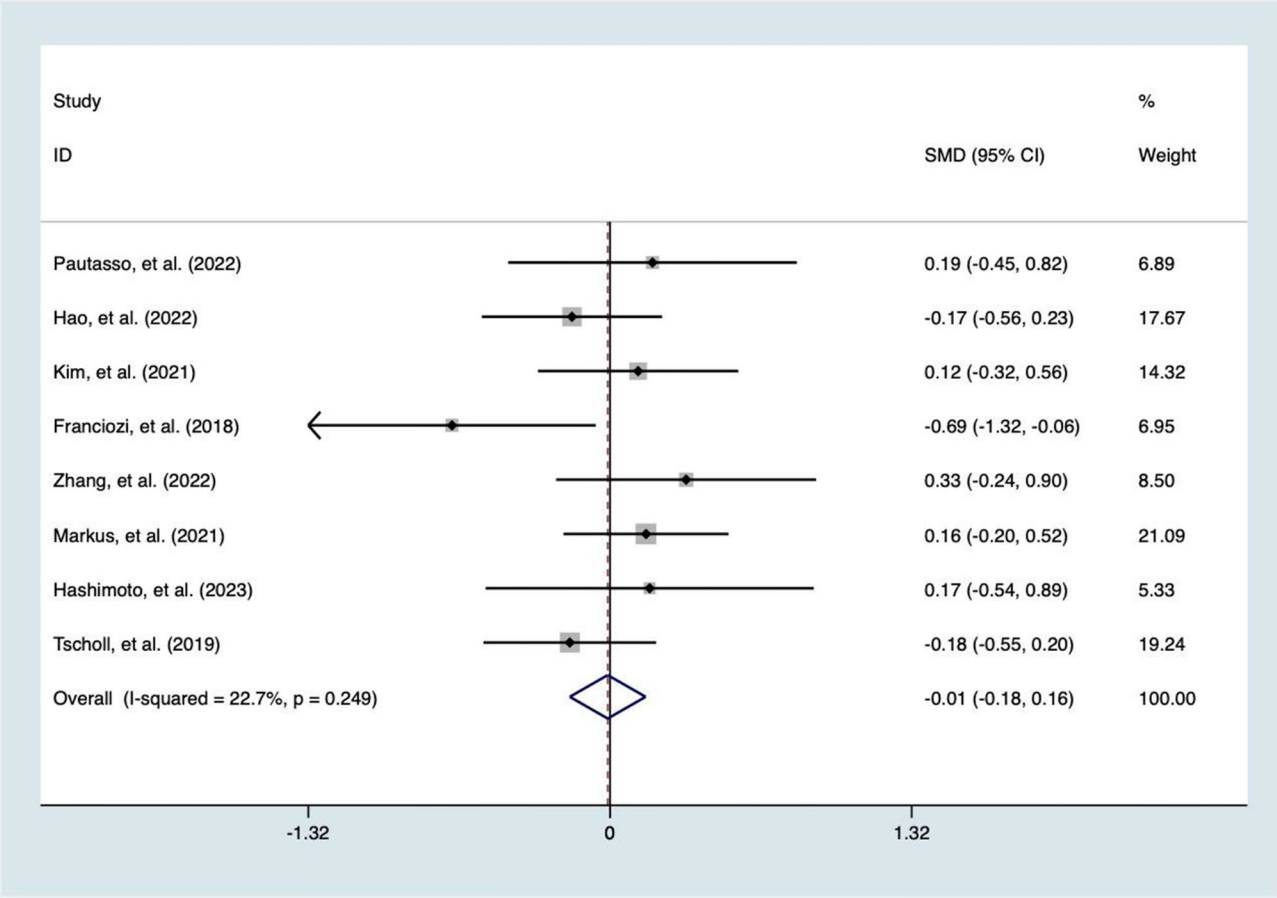

Fig. 2 Forest plot compared the post-operative Kujala scores between iMPFLR and MPFLR + TTO, with associated 95% confidence intervals

Characteristics of subjects

This systematic review included 715 participants, comprising 224 males and 491 females, divided into a control group (undergoing only iMPFLR, with a total of 389 knees) and an experimental group (undergoing MPFLR + TTO, with a total of 337 knees). The control group had an average age of 22.5 years (95% CI [22.1–22.8]), with an average follow-up time of 40.2 months (95% CI [37.6–42.8]). The proportion of patients with severe trochlear dysplasia (Dejour classification types B, C, and D) was 68.3% (95% CI [67.3-69.3%]), and the average preoperative TT-TG was 16.1 mm (95% CI [15.8–16.3]). The experimental group had an average age of 22.7 years (95% CI [22.4–23.0]), with an average follow-up time of 36.4 months (95% CI [34.3–38.5]). The proportion of patients with severe trochlear dysplasia was 79.1% (95% CI [77.5-80.7%]), and the average preoperative TT-TG was 20.2 mm (95% CI [20.0-20.4]). The results indicate that the average preoperative TT-TG value in the control group is significantly lower than that in the experimental group. In the studies by Franciozi et al. and Zhang et al., the TT-TG values of the two groups remained consistent (with Franciozi's inclusion criteria being 17 < TT-TG < 20 mm and Zhang's criteria being 15 < TT-TG < 20 mm). Two studies excluded cases of excessive knee valgus [15, 16]. Zhang et al. excluded patients with severe cartilage damage (all patients had Outerbridge grade < 3) [15], while Tscholl et al. excluded patients with severe PFOA (all patients had Sperner score ≤ 3) [16]. Additionally, two studies indicated that the cartilage condition in the control group was better than in the experimental group [17, 18]. Except for Markus's study, all other studies included patients primarily with recurrent patellar dislocation (RPD) (with episodes ≥ 2, often accompanied by positive apprehension tests), while Hashimoto et al. also included habitual patellar dislocation, trochlear dysplasia, and high-riding patella in their study [18]. Additionally, seven studies reported preoperative Kujala scores for both groups, four studies reported preoperative Lysholm scores, and four studies reported preoperative Tegner scores. The average Kujala score in the control group was 54.2 (95% CI [53.1–55.2]), the average Lysholm score was 46.7 (95% CI [45.9–47.4]), and the average Tegner score was 4.1 (95% CI [3.9–4.2]). The average scores for the experimental group were 52.6 (95% CI [51.6–53.6]), 45.5 (95% CI [44.7–46.3]), and 3.5

(95% CI [3.3–3.6]), respectively. The baseline data for each study are shown in the preoperative data sections of Tables 4 and 5.

Surgical and rehabilitation protocols

All studies conducted a preoperative arthroscopic examination to assess articular cartilage damage, and additional lateral soft tissue release was performed when necessary, which is recognized as having no impact on postoperative prognosis. In the MPFLR portion, five studies used the semitendinosus tendon for the graft, four used the gracilis tendon, and one study referred to the the Schöttle point and the bony landmarks of the medial epicondyle and adductor tubercle of the femur for femoral side positioning, with one study noting graft fixation at 20° of knee flexion [19], and another three reporting fixation at 60° of knee flexion [17, 18, 20]. Most studies opted to combine TTO when the preoperative TT-TG was large or combined with high-riding patella, with TTO being performed before MPFLR graft fixation. Among these, three studies conducted medial transfer of the tibial tubercle when TT-TG was >20 mm [18, 19, 21], 2 when >15 mm [16, 22], mostly transferring to 10–12 mm; 4 studies mentioned distal transfer of the tibial tubercle when CDI was >1.2 [15–17, 19], and if both conditions were present, they tended to select the anteromedial transfer method. The fixation of the osteotomy block was primarily with 2–3 cortical bone screws. Almost all patients wore a hinged keen brace immediately postoperatively and performed ankle pump exercises. In most studies, the iMPFLR group was allowed immediate passive flexion and partial weight-bearing training postoperatively, with 2 studies starting at 1–2 weeks [15, 18]; all studies had the iMPFLR group completely off crutches by 6–8 weeks. The combined group delayed the above training time points by 4–6 weeks compared to the iMPFLR group.

Evaluation metrics

Xu et al.'s study had a shorter follow-up time for the control group, which necessitated comparing short-term follow-up results for the experimental group to reduce potential confounding bias [23]. The remaining postoperative functional scores were obtained from the last follow-up data of each study. Through meta-analysis, it was observed that 80% of the studies reported postoperative Kujala scores, with the overall average for the control group being 85.1 (95% CI [84.4–85.9]) and for the experimental group being 85.4 (95% CI [84.9–85.9]), indicating low inter-group heterogeneity (I^2=22.7%). The forest

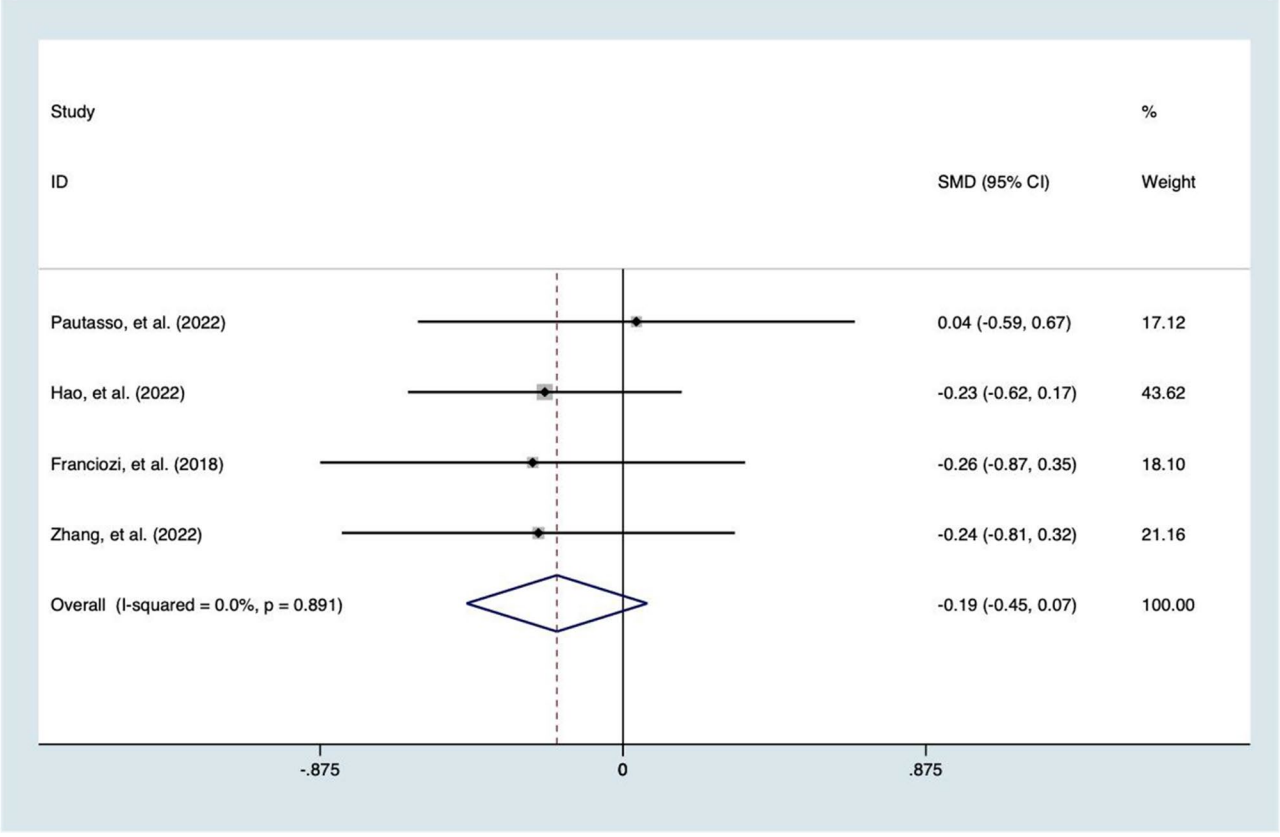

Fig. 3 Forest plot compared the post-operative Lysholm scores between iMPFLR and MPFLR + TTO, with associated 95% confidence intervals

Table 4 Baseline data of study

Author	Type	*N*° patients		iMPFLR/MPFLR+TTO (*N*° knees)	Mean age (years)	BMI (kg/m^2)	Trochlear dysplasia type	Follow up (months)	Cartilage lesion or PFOA	Characteristic of disease	LOE
		Male	Female								
Pautasso, et al. [19]	Retrospective	12	28	15/27	27.6 ± 5.9/21.5 ± 2.9	NA	NA	32.6 ± 11.7/35.4 ± 9.1	NA	RPD: *n* = 37 Primary: *n* = 3	IV
Hao, et al. [21]	Retrospective	18/22	30/29	48/51	20.7 ± 7.6/20.7 ± 5.7	23.3 ± 3.7/24.2 ± 4.6	NA	26.0 ± 11.3/24.9 ± 10.8	NA	At least 2 episodes of PD or PFI with positive apprehension sign	IV
Kim, et al. [22]	Retrospective cohort	16/26	20/19	36/45	20.7 ± 6.3/23.3 ± 9.1	25.9 ± 5.3/24.2 ± 12.3	None or A: 17%/31% B, C or D: 83%/69%	28.2 ± 13.6/22.6 ± 10.8	NA	At least 2 episodes of PD	III
Perkins, et al. [24]	Retrospective	29	45	45/33	15.1/15.8	23.7/22.5	None or A: 24%/12% B, C or D: 76%/88%	36.0	NA	90% of all patients with at least 2 episodes of PD (MPFLR+TTO group were significantly higher)	III
Franciozi, et al. [17]	Prospective cohort	8/3	16/15	24/18	28 ± 8.6/25.3 ± 7.5	NA	None or A: 42%/39% B, C or D: 58%/61%	40.5 ± 11.6/41.3 ± 10.3	All subjects have and majority were lateral facet and distal portion of ridge, outbridge grade 1 ~ 2: 12/9 3 ~ 4:12/9	At least 2 episodes of PD or PFI with positive apprehension sign, with 17 < TT-TG < 20, but not patellar lesions of Outerbridge grade 3 ~ 4 involving medial facet or proximal region and CDI > 1.4	II
Zhang, et al. [35]	Retrospective cohort	10/3	26/15	36/18	21.5 ± 4.3/23.2 ± 5.6	NA	None or A: 36%/22% B, C or D: 64%/78%	85.2 ± 17.5/81.6 ± 15.4	Patellar lesions of Outerbridge grade < 3	At least 2 episodes of PD with 15 < TT-TG < 20 exclude genu valgum > 10°, congenital or habitual PD	III
Markus, et al. [20]	Retrospective	14/14	45/45	59/59	25.0 ± 9.0/25.0 ± 8.9	NA	NA	49.0 ± 27.0/49.0 ± 27.9	NA	NA	III
Hashimoto, et al. [18]	Retrospective cohort	4/4	10/12	14/16	19.6 ± 6.3/27.8 ± 11.2	NA	None or A: 79%/19% B, C or D: 21%/81%	60 ± 34.8	Iwano PFOA grade 0 ~ 1: 100%/19% 2 ~ 4: 0%/81%	RPD or habitual PD including cases of trochlear dysplasia and patella alta, but not congenital PD	III

Table 4 (continued)

Author	Type	N° patients		iMPFLR/MPFLR+TTO (N° knees)	Mean age (years)	BMI (kg/m²)	Trochlear dysplasia type	Follow up (months)	Cartilage lesion or PFOA	Characteristic of disease	LOE
		Male	Female								
Tscholl, et al. [16]	Retrospective	16/14	56/29	72/43	25.2 ± 9.5/22.9 ± 7.1	NA	None or A: 31%/7% B, C or D: 68%/93% 1 is NS	5.4 ± 3.1(years)	No advanced PFOA (≤grade 3 according to the Sperner score)	RPD (in daily activities, without trauma, range 2–10) and no genu valgum > 5°	III
Xu, et al. [35]	Retrospective	12	28	40/27	22.7 ± 7.8/24.3 ± 7.9	NA	None or A: 20%/15% B, C or D: 80%/85%	1.43/1.77 ± 1.1 & 6.51 ± 1.57(short & mid-term, years)	NA	At least 2 episodes of PD or PFI with positive apprehension sign and Q angle > 15°	III

Note The trochlear types are all Dejour type. All continuous variables are expressed in the form of Mean±SD, and categorical variables are expressed as rates. Unless otherwise specified, the data order is all iMPFLR/MPFLR+TTO. Some data lack grouped data, so only the overall study data is represented

plot results are illustrated in Fig. 2.; 40% of the studies reported postoperative Lysholm scores, with the control group averaging 89.4 (95% CI [88.9–89.9]) and the experimental group averaging 89.1 (95% CI [89.0-89.3]), showing minimal inter-group heterogeneity (I^2=0%). The forest plot results are illustrated in Fig. 3. The average postoperative TT-TG value for the control group was 14.6 mm (95% CI [14.3–15.0]), while for the experimental group, it was 12.0 mm (95% CI [11.8–12.2]), with significant inter-group heterogeneity (I^2=93.3%), indicating that the control group had higher values than the experimental group. The forest plot results are illustrated in Fig. 4.

Recurrent Patellar Dislocation (RPD) was considered a primary indication of surgical failure. Furthermore, persistent recurrent patellar instability, a positive apprehension test, and abnormal J-sign were regarded as potential risks for the recurrence of patellar dislocation (PD). The purpose of the surgery was also to address these issues, thus the presence of these abnormal signs was also deemed as surgical failure. The results showed that the average surgical failure rate for the control group was 5.1% (95% CI [4.7–5.6]), while for the experimental group, it was 3.2% (95% CI [3.0-3.4]), with an odds ratio (OR) of 2.18 (95% CI [1.05–4.53], I^2=0%, p=0.738), indicating no significant difference between the groups. The forest plot results are illustrated in Fig. 5. Moreover, the reoperation rate for the control group was 1.9% (95% CI [1.6–2.2]), compared to 10.7% (95% CI [9.4–12.1]) for the experimental group, with an OR of 0.12 (95% CI [0.03–0.54], I^2=63.1%, p=0.028), showing that the experimental group had a significantly higher rate than the control group. The forest plot results are illustrated in Fig. 6. Specifically, the control group had 2 cases of debridement after infection [24], 5 cases of knee joint release under anesthesia [17, 20], and 1 case of TTO [20]. In contrast, the experimental group had 34 cases of internal fixation screw removal [15–17, 20, 24], 1 case of cartilage repair [24], 2 cases of debridement after infection [15, 20], 1 case of knee joint release under anesthesia [15], and 1 case of total knee arthroplasty [20]. Regarding other complications, there was 1 case of postoperative patellar fracture in the control group [22]. Hashimoto et al.'s study reported on postoperative PFOA, with 3 cases in the control group and 1 case in the experimental group [18].

Discussion

This systematic review evaluates the differences and similarities between isolated medial patellofemoral ligament reconstruction (iMPFLR) and MPFLR combined with tibial tuberosity osteotomy (MPFLR+TTO) in treating PFI. All studies reported good mid-term and short-term outcomes for both surgical methods. A significant finding from this review is that there were no marked differences in postoperative knee function and surgical

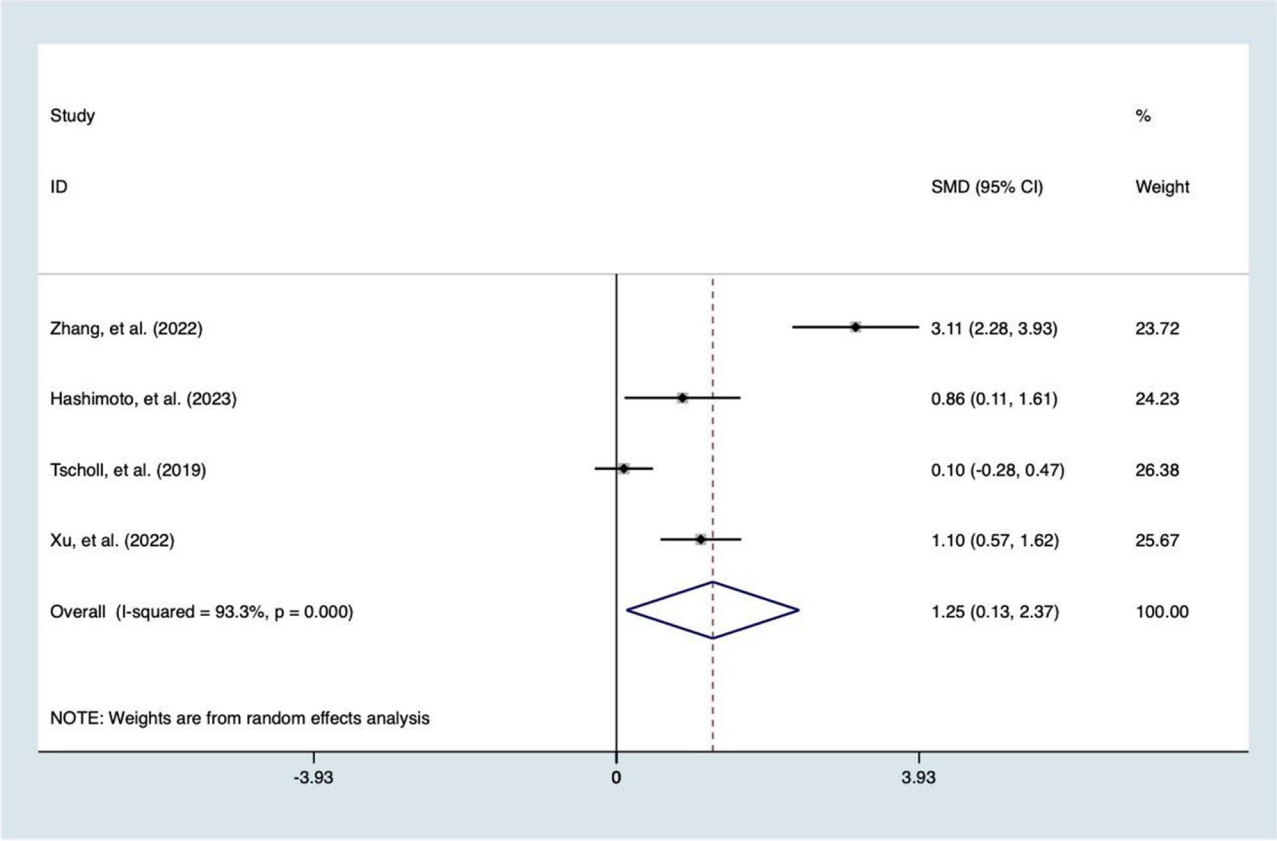

Fig. 4 Forest plot compared the post-operative TT-TG between iMPFLR and MPFLR + TTO, with associated 95% confidence intervals

failure rates between the two groups. The incidence and types of complications were similar; however, the reoperation rate was significantly higher in the experimental group. Furthermore, since the surgical indications for the two groups were not identical, the comparison of surgical outcomes was based on preoperative baselines that were not completely balanced. Thus, efficacy comparison should consider the preoperative epidemiological and anatomical characteristics of the patients.

The studies included in this review utilized various displacement methods of TTO, including medial, distal, and combined approaches. Most studies adopted the TT-TG > 20 mm criterion proposed by Dejour as an indication for TTO [11], which resulted in significant differences in preoperative average TT-TG values between the two groups. Based on knee biomechanics, an excessively large TT-TG value when using only iMPFLR can increase the tension on the graft, leading to patellofemoral joint overload during the first half of knee flexion [25–27]. Franciozi et al. and Zhang et al. maintained consistent preoperative TT-TG values between the two groups (17–20 mm vs. 15–20 mm). Franciozi et al. supports the combination of TTO within this TT-TG range, while Zhang et al. opposes it, citing longer follow-up periods. Their results indicated that postoperative knee function was similar between the two groups [17], but the experimental group experienced a higher reoperation rate [15]. In our view, TT-TG < 20 mm remains a major controversy regarding the choice of TTO surgery, suggesting that iMPFLR cannot be directly selected without further evaluation. Preoperative assessment of trochlear morphology can help address the J-sign issue. Intraoperatively, dynamic examination of the knee joint through arthroscopy and patellar translation can assess the pressure between the patellofemoral joint. Four studies chose distal tibial tubercle displacement in patients with CDI > 1.2 in the experimental group. Zhang et al. and Tscholl et al. suggest that iMPFLR itself has a certain degree of patellar lowering effect, with the latter reporting similar failure rates and knee function scores for both surgeries [15, 16]. Franciozi et al., however, indicated that the absence of distal tibial tubercle displacement in patients with CDI > 1.2 in the control group might explain the lesser improvement in Kujala scores compared to the experimental group. Although a high patella increases the distance the patella travels before entering the trochlear groove during knee flexion, thereby increasing the likelihood of dislocation [5, 28], the preoperative differences in CDI between the two groups in the mentioned studies were not significant. The studies did not report

extreme values of excessively high CDI. We consider that differences in patellar height are not a key factor affecting surgical outcomes. Additionally, the included studies were all mid-term follow-ups, during which the grafts should still maintain good tension, playing a certain role in counteracting the tendency of the patella to dislocate during movement.

Many studies have reported failure cases even after realignment of the knee extension force line and improvement of patellar positioning. Although the average failure rate in the control group (5.1%) was slightly higher than in the experimental group (3.2%, $p=0.738$), the control group exhibited a greater proportion of postoperative residual positive signs. The rates of redislocation were quite similar between both groups, which does not fully align with the performance of knee joint function. This discrepancy is likely due to the complex anatomical structure surrounding the patellofemoral joint, prompting further investigation into trochlear morphology in these studies. Seven studies reported classifications of preoperative trochlear dysplasia in both groups. Except for Hashimoto's study, which found a higher proportion of mild trochlear dysplasia in the control group [18], the remaining studies indicated that severe trochlear dysplasia was more prevalent in both groups. Moreover, baseline statistical results showed a significant difference in the severity of trochlear dysplasia between the groups, with a higher prevalence in the experimental group[15–17,22–24]. Research suggests that patients with severe trochlear dysplasia undergoing iMPFLR treatment have a recurrence rate four times higher than those treated with combined TTO, and for the same surgical procedure, the recurrence rate in patients with severe trochlear dysplasia remains 2–3 times higher than in those with mild dysplasia [6, 29]. Therefore, considering trochlear dysplasia as an indication for TTO may yield better outcomes compared to iMPFLR, and for cases of extreme trochlear dysplasia, an additional trochleoplasty might be a more reasonable approach [30]. In fact, when assessing TT-TG measurements in conjunction with trochlear dysplasia, the location of the trochlear groove's low point appears closer to the distal end on CT scans, often resulting in measurements that are lower than normal, which can influence the choice of surgical procedure

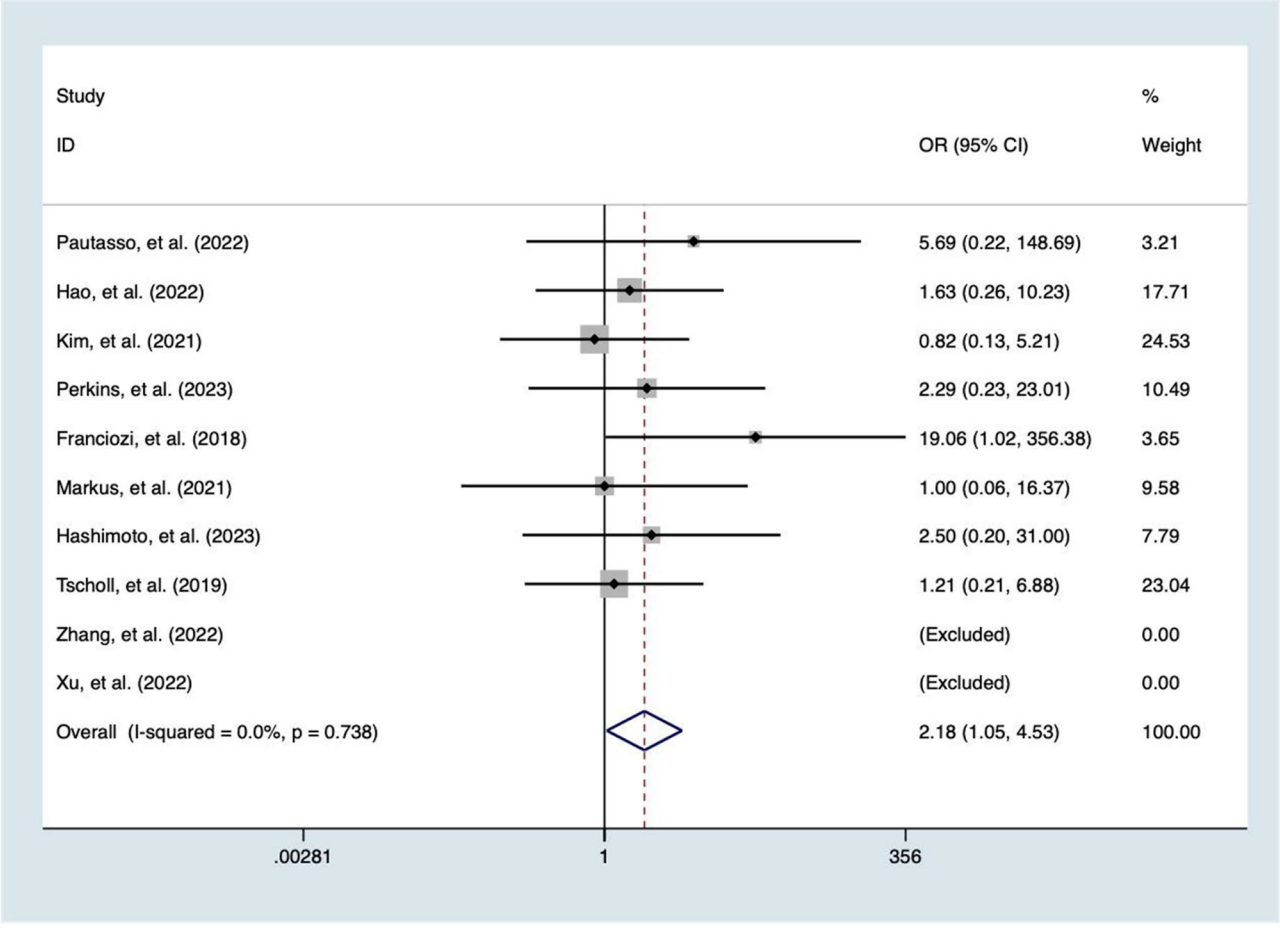

Fig. 5 Forest plot compared the odd ratio of post-operative failure rate between iMPFLR and MPFLR + TTO, with associated 95% confidence intervals

Table 5 Details of study

Author	Surgical modality		Mean preoperative data					Mean post operation data				
	MPFLR	TTO	Kujala	Lysholm	Tegner	TT-TG	CDI	Kujala	Lysholm	Tegner	TT-TG	Salient findings
Pautasso, et al. [19]	Gracilis autograft (Schöttle)	If TT-TG > 20 or CDI > 1.2 Elmslie-Trillat: *n* = 10 Distalization: *n* = 8 Distal-medialization: *n* = 9	47.8 ± 8.3/47.1 ± 7.6	48.3 ± 9.5/44.1 ± 8.9	3.3 ± 0.8/2.9 ± 0.7	NA	NA	91.1 ± 14/88.5 ± 13.5	90.1 ± 14.8/89.6 ± 11.9	4.8 ± 1.4/4.9 ± 1.7	NA	RPD: iMPFLR (*n* = 1).
Hao, et al. [21]	Semitendinosus autograft	TT-TG > 20 Medialization to TT-TG < 20	62.2 ± 8.1/60.9 ± 9.2	49.9 ± 4.8/48.8 ± 6.2	3.5 ± 0.9/3.1 ± 1.0	16.5 ± 2.6/ 22.2 ± 4.3	NA	85.2 ± 5.8/86.1 ± 5.0	87.7 ± 3.3/88.4 ± 2.9	5.4 ± 1.2/5.1 ± 1.2	15.1 ± 4.2 (TTO)	Women have worse post-op clinical functional and pain assessments than men. RPD: iMPFLR (*n* = 3), MPFLR + TTO (*n* = 2), no one has positive apprehension sign. Combined group have more post-op pain, most of them are due to fixation devices.
Kim, et al. [22]	Semitendinosus or tibialis anterior autograft (Schöttle)	15 < TT-TG < 25 Medialization to TT-TG < 10	57.2 ± 22.7/56.0 ± 16.2	NA	3.5 ± 2.3/3.6 ± 1.7	20.5 ± 4.7/21.7 ± 2.1	NA	90.5 ± 10.6/89.3 ± 9.0	NA	4.5 ± 1.8/4.6 ± 1.1	NA	Post-op functional failure: iMPFLR (*n* = 2 with instability), MPFLR + TTO (*n* = 3, 1 with RPD and 2 with instability), 2 of them with trochlear type D, 2 with A and 1 with B, 1 of them with functional failure has TT-TG < 20 as others > 20. Patella fracture: iMPFLR (*n* = 1).
Perkins, et al. [24]	Gracilis allograft (adductor tubercle auxiliary location)	TT-TG > 18/borderline TT-TG (16–18) with j-tracking or high-grade trochlear dysplasia (type C or D) Medialization to about 10	NA	NA	NA	15.4 (12.7,17.3)/ 19.0 (13.9,22.3)	0.83 (0.75,0.93)/ 0.87 (0.80,1.02)	98 (76,100)/96 (74,98)	95 (82,100)/94 (83,95)	7 (5,9)/5 (4,7)	No revision: 15.82 (13.38,19.69)/ Revision: 18.02 (15.85,19.56)	RPD: iMPFLR (*n* = 3), MPFLR + TTO (*n* = 1). Secondary surgeries for noninstability: MPFLR + TTO: removing symptomatic TTO screw in MPFLR + TTO (*n* = 7), removing headless compression screws (*n* = 2) Late repair of cartilage injury (*n* = 1) iMPFLR: infection debridement (*n* = 2)

Table 5 (continued)

Author	Surgical modality		Mean preoperative data					Mean post operation data				
	MPFLR	TTO	Kujala	Lysholm	Tegner	TT-TG	CDI	Kujala	Lysholm	Tegner	TT-TG	Salient findings
Franciozi, et al. [17]	Semitendinosus autograft (adductor tubercle auxiliary location)	Anteromedialization to 10 < TT-TG < 12 and distalization when 1.2 < CDI < 1.4	58.7 ± 6.1/57.3 ± 4.9	49.4 ± 6.7/47.1 ± 9.0	5.5 ± 1.2/5.2 ± 1.3	18.0 ± 1.1/18.5 ± 1.2	1.12 ± 0.11/ 1.12 ± 0.14	82.7 ± 8.1/87.6 ± 5.4	85.6 ± 7.4/87.6 ± 8.0	5.2 ± 1.3/5.1 ± 1.4	10.55 ± 0.83 (MPFLR + TTO)	Residual J sign post-op: iMPFLR ($n = 8$),2 of them with normal patellar height and 6 with patella alta. Combined group is better than iMPFLR in patella track, none of subjects had positive apprehension test and RPD. Secondary surgeries: Removing tibial tubercle screws in MPFLR + TTO ($n = 2$). Manipulation under anesthesia in iMPFLR ($n = 1$).
Zhang, et al. [35]	Semitendinosus autograft (Schöttle)	Anteromedialization to 10 < TT-TG < 12 and distalization when CDI > 1.2	37.6 ± 5.9/34.9 ± 7.9	39.8 ± 8.3/36.5 ± 6.8	NA	16.6 ± 1.4/17.1 ± 1.5	1.16 ± 0.13/ 1.18 ± 0.12	84.5 ± 5.1/82.9 ± 4.1	88.3 ± 9.9/90.6 ± 8.3	NA	16.2 ± 1.9/ 10.4 ± 1.8	Secondary surgeries: MPFLR + TTO: removing internal fixation devices ($n = 7$), arthrolysis ($n = 1$), infection debridement ($n = 1$).
Markus, et al. [20]	Gracilis autograft (Schöttle)	Anteromedialization	NA	NA	NA	14.1 ± 2.8/19.8 ± 3.9	NA	86.3 ± 13.3/83.9 ± 16.9	NA	NA	NA	Post-op RPD in iMPFLR ($n = 1$), MPFLR + TTO ($n = 1$). Secondary surgeries: iMPFLR: MUA ($n = 4$), TTO ($n = 1$). MPFLR + TTO: removal of hardware ($n = 3$), irrigation and debridement($n = 1$), TKA($n = 1$).
Hashimoto, et al. 18	Semitendinosus autograft (adductor tubercle auxiliary location)	Anteromedialization when TT-TG > 20, PFJ space narrowing or habitual PD	68.4 ± 10.1/55.5 ± 9.3	NA	NA	17.9 ± 3.0/21.0 ± 3.1	NA	94.9 ± 6.0/93.8 ± 6.6	NA	NA	16.2 ± 2.4/ 13.7 ± 3.3	No RPD case and post-op apprehension test (+) in iMPFLR ($n = 2$), MPFLR + TTO ($n = 1$), post-op patellofemoral arthritis in iMPFLR ($n = 3$), MPFLR + TTO ($n = 1$).

Table 5 (continued)

Author	Surgical modality		Mean preoperative data					Mean post operation data				
	MPFLR	TTO	Kujala	Lysholm	Tegner	TT-TG	CDI	Kujala	Lysholm	Tegner	TT-TG	Salient findings
Tscholl, et al. [32]	Gracilis autograft (adductor tubercle auxiliary location)	Distal-medialization to CDI ≤ 1.1 and 10 < TT-TG < 12 when patellar maltracking or persistent patellar subluxation and either increased TT-TG > 15 or CDI > 1.2	52.7 ± 28.8/47.0 ± 29.5	NA	NA	13.2 ± 5.4/18.2 ± 5.4	1.05 ± 0.13/1.18 ± 0.15	74.0 ± 19.9/77.2 ± 14.7	NA	NA	12.1 ± 5.0/11.6 ± 5.5	Post-op RPD in iMPFLR (*n* = 2), MPFLR + TTO (*n* = 1), recurrent subluxation in iMPFLR (*n* = 2), MPFLR + TTO (*n* = 1). Secondary surgeries: Removal of lag screws in MPFLR + TTO (*n* = 13) A positive post-op apprehension test (*n* = 6) was not associated with an increased incidence of RPD
Xu, et al. [35]	Subjects TT-TG > 15 belong to subgroup in iMPFLR	NA	NA	NA	NA	17.4 ± 4.3/21.0 ± 1.6	1.19 ± 0.17/1.23 ± 0.20*	95 & 95.5(iMPFLR & iMPFLR subgroup)/86 & 95(short and mid-term)	94.5 & 92.5(iMPFLR & iMPFLR subgroup)/90 & 95(short and mid-term)	NA	17.3 ± 4.3 & 19.8 ± 2.9(iMPFLR & iMPFLR sub-group)/12.8 ± 3.8 &12.8 ± 3.8(short and mid-term)	No RPD case

Note All continuous variables are expressed in the form of Mean ± SD or Median (IQR), and categorical variables are expressed as rates. Unless otherwise specified, the data order is all iMPFLR/MPFLR + TTO. Some data lack grouped data, so only the overall study data is represented. For some individual studies, subgroup data is used and has been explained in the table. The postoperative data, unless otherwise specified, are all from the last follow-up. *Insall-Salvati index

[31, 32]. TT-TG measurements are also affected by factors such as femoral or tibial rotation. Tensho et al. indicated that the increase in TT-TG due to these factors is significantly greater than that caused by mere displacement of the tibial tuberosity [33]. Recent studies have employed updated metrics, such as the tibial tuberosity-posterior cruciate ligament distance (TT-PCL) [34] and the tibial tubercle-Roman arch distance (TT-RA), which substantially reduce the impact of trochlear morphology and lower limb rotation on measurements [35].

From the statistical results on prognosis, mid-term and short-term knee function scores were generally consistent between the two groups. Studies indicate that complication rates following TTO surgery range from 4 to 7%,. These include tibial fractures (1–3%), delayed bone segment healing (approximately 1%), and deep vein thrombosis (around 4%) [10, 36]. The studies reviewed did not report these complications, except for surgical failures and a higher rate of secondary surgeries, primarily involving proactive removal of internal fixation screws in the experimental group. Hao et al. examined postoperative quality of life in both groups, finding that TTO did not reduce this quality [21]. However, the overall recovery process was slower in the experimental group, attributed to surgical type and rehabilitation protocols. While a delayed recovery may reduce pain and aid in bone and incision healing, it increases the risk of postoperative complications. Thus, protecting bony structures, vascular nerves, and tendinous tissues during TTO surgery is crucial.

In research by Hashimoto et al., progression of patellofemoral osteoarthritis (PFOA) was evaluated, showing a lower incidence of postoperative patellofemoral arthritis in the experimental group [18]. Other studies did not explicitly address this issue, which may relate to follow-up duration; PFOA is considered a late complication, while most included studies had medium to short follow-up periods. Patients with postoperative progression of PFOA exhibited greater patellar tilt and congruence angles, possibly due to excessive graft tension during MPFLR [37]. Furthermore, an excessively large TT-TG distance can increase lateral tension on the patella, causing overload on the patellofemoral joint. Consequently, TTO is often performed prior to securing the graft in MPFLR to balance the patella's lateral forces under normal Q angles.

For PFI patients, MPFLR is the standard treatment according to the International Patellofemoral Study Group [22], but it addresses only soft tissue damage. Cases with concurrent bony abnormalities may require TTO or other interventions [38, 39]. There is no universal solution for PFI patients; clinicians must analyze whether patients have bony structural abnormalities to consider a combined TTO for improved outcomes.

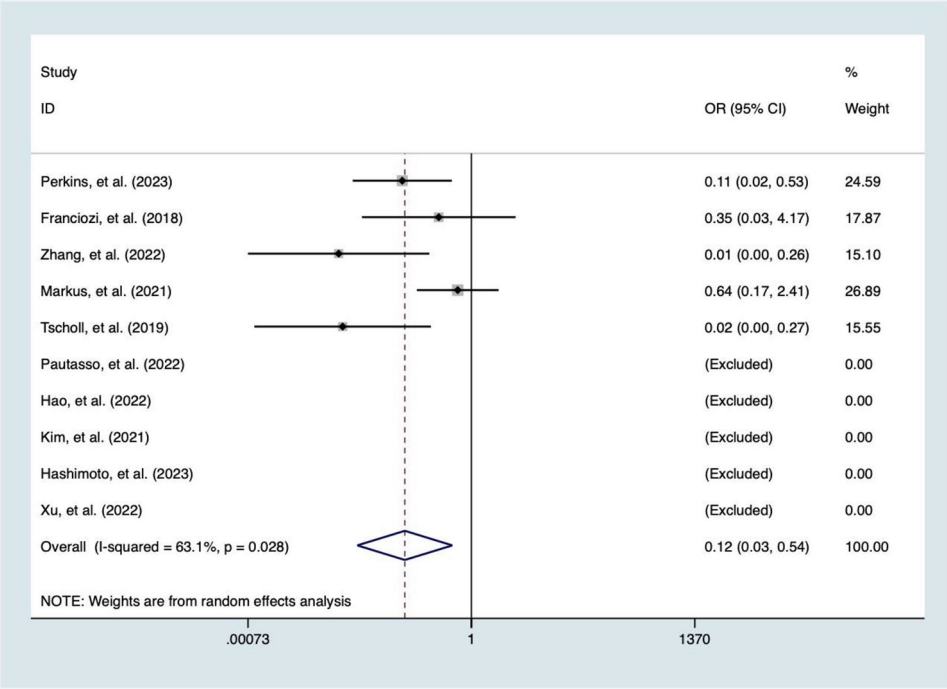

Fig. 6 Forest plot compared the odd ratio of secondary operation rate between iMPFLR and MPFLR + TTO, with associated 95% confidence intervals

Limitations

The limitations of this review relate primarily to the quality of the included studies. Firstly, the retrospective nature of most studies may weaken the evidence. Secondly, variations in inclusion and exclusion criteria across studies are evident, involving factors such as types of patellar dislocation, presence of preoperative cartilage damage, and classifications of trochlear dysplasia. Furthermore, differences in indications for iMPFLR versus combined procedures with TTO complicate subject randomization across studies, resulting in imbalanced baselines between groups. Thirdly, the included studies primarily feature medium to short follow-up periods, with a lack of long-term follow-up research. Fourthly, the inability to conduct postoperative outcome measurements under blinded conditions prevents the avoidance of measurement bias. Finally, inconsistencies in prognostic evaluation metrics across studies limit horizontal comparisons.

Conclusion

Compared to iMPFLR, combining MPFLR with TTO to treat PFI achieves equally effective postoperative knee function, without increasing the failure rate or incidence of adverse events. However, the combined use of TTO may prolong the postoperative rehabilitation process and necessitate the removal of internal fixation devices, thereby increasing the rate of secondary surgeries. For cases featuring malalignment of the extensor mechanism or abnormal patellar position, combining TTO is recommended to ensure a favorable prognosis.

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Author contributions

All authors contributed to the study conception and design. Material preparation, data collection and analysis were performed by Zhixue Wang, Peng Wu and Zhenwei Ji. The first draft of the manuscript was written by Xiangyu Meng and Huanming Fang and Peng Zhao. All authors commented on previous versions of the manuscript, read and approved the final manuscript. Xiangyu Meng was identified as the first author, Zhixue Wang and Yong Ding were identified as the corresponding authors of the manuscript.

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Data availability

No datasets were generated or analysed during the current study.

Declarations

Ethics approval

This study is a meta-analysis that integrates data from previously published studies, without direct participate in or interaction with human or animal subjects. According to the guidelines and criteria for meta-analyses, this type of study does not require ethical approval.

Consent for publication

Not applicable.

Competing interests

The authors declare no competing interests.

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