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Research Article

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Posted Date: September 23rd, 2026

DOI: <https://doi.org/10.21203/rs.3.rs-10841275/v1>

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Additional Declarations: No competing interests reported.

Biomechanical and clinical evaluation of full arthroscopic native femoral footprint localization for MPFL reconstruction: Verification of a 3-mm three-dimensional deviation tolerance threshold

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Abstract

Objective To compare the patellofemoral biomechanical performance between full visualization femoral insertion (FVFI) and traditional Schöttle-point fluoroscopic insertion (TPFI) for medial patellofemoral ligament (MPFL) reconstruction, and to clinically verify the safe three-dimensional (3D) deviation threshold of femoral tunnels.

Methods An idealized patellofemoral finite element (FE) model was constructed based on CT data of a patient with Dejour type A trochlear dysplasia and normal patellar height. Two FE groups were established: FVFI (native footprint tunnel) and TPFI (Schöttle-point tunnel). Patellar lateral translation, peak femoral tunnel stress and average patellofemoral contact pressure were quantified at 0°, 30°, 60° and 90° knee flexion angles. A single-center retrospective cohort of 34 patients who underwent FVFI-MPFL reconstruction combined with lateral retinacular release between Jan 2024 and Oct 2025 was enrolled. All patients were stratified by

postoperative 3D CT-measured femoral tunnel deviation: precise group (deviation ≤ 3 mm, $n=28$) and general group (deviation > 3 mm, $n=6$). Baseline demographics, knee range of motion (ROM), Kujala and Lysholm scores at 1, 3 and 6 months postoperatively, redislocation rate and 6-month patient satisfaction were collected. Repeated-measures analysis of covariance (ANCOVA) was applied with preoperative dislocation times as a covariate; Spearman rank correlation was used to analyze the association between tunnel deviation and functional scores.

Results The absolute values of patellar lateral translation in both FE groups were less than 1.0 mm across all flexion angles, within the physiological safe range. No obvious differences in contact pressure and tunnel stress were observed at 0° and 30° , while the TPFL group exhibited significantly higher peak femoral tunnel stress at 60° and 90° . After covariate correction, there were no significant intergroup differences in postoperative ROM and redislocation rate. The precise group achieved significantly superior Kujala, Lysholm scores and 6-month subjective satisfaction (all $P<0.05$). A moderate weak negative correlation was detected between femoral tunnel deviation and 6-month Kujala score ($r_s = -0.339$, $P = 0.050$).

Conclusion Full arthroscopic native femoral footprint localization reduces peak femoral tunnel stress during deep knee flexion. When the 3D femoral tunnel deviation is controlled within 3 mm, patients obtain better mid-term knee function and subjective satisfaction. The 3-mm deviation threshold provides reliable biomechanical and clinical evidence for intraoperative quality control in MPFL reconstruction.

Keywords: Recurrent patellar dislocation; Medial patellofemoral ligament reconstruction; Femoral tunnel; Finite element analysis; Position deviation; Tolerance threshold

1 Introduction

1.1 Research Background

Recurrent patellar dislocation predominantly occurs in adolescents and severely impairs knee function. Medial patellofemoral ligament (MPFL) rupture is the primary pathological cause of persistent patellar instability. Non-operative management yields

a redislocation rate of approximately 40%^[1]. As the primary soft tissue restraint against lateral patellar translation, the MPFL provides 60%–80% of stabilizing force at 0°–30° knee flexion^[2]; thus, MPFL reconstruction has become the gold-standard surgical treatment for patellofemoral instability^[3,4]. Precise femoral tunnel placement is the core determinant of surgical outcomes, as malposition induces abnormal patellofemoral contact pressure, graft length mismatch, and subsequent complications including recurrent dislocation and chondral wear^[5–7].

Conventional TPFJ relies on radiographic landmarks on lateral knee radiographs: 1.3 mm anterior and 2.5 mm distal to the intersection of the perpendicular line of the posterior Blumensaat line and the posterior medial femoral condyle margin^[8]. Despite widespread adoption, fluoroscopy-based positioning has critical limitations: a mere 2.5° projection error generates a tunnel deviation exceeding 5 mm, and Schöttle's landmark does not anatomically coincide with the native MPFL femoral footprint^[9,10]. Full visualization femoral insertion (FVFI) directly identifies the adductor tubercle and native MPFL footprint under arthroscopic visualization, minimizing fluoroscopic radiation and improving placement accuracy^[11]. This technique confers additional benefits including reduced postoperative pain and accelerated rehabilitation, particularly in obese patients with thick subcutaneous adipose tissue^[12]. Nevertheless, the biomechanical tolerance threshold of FVFI to tunnel deviation and its correlation with mid-term clinical outcomes remain poorly characterized, lacking integrated evidence linking mechanical mechanisms to real-world clinical performance.

1.2 Literature Review

Anatomical studies confirm that the native MPFL femoral footprint lies on the bony ridge between the medial epicondyle and adductor tubercle, 8 mm distal to the apex of the adductor tubercle and 8 mm from the posterior border of the femur^[13].

Cadaveric biomechanical experiments demonstrate that femoral tunnels positioned proximal or distal to the native footprint significantly elevate patellofemoral contact pressure, patellar tilt and lateral translation during knee flexion/extension^[6,14]. A tunnel deviation exceeding 5 mm induces substantial graft length variation, increased graft tension and medial compartment pressure, raising the risk of graft laxity^[15].

Finite element modeling is a mainstream tool for MPFL biomechanical assessment. DeVries Watson et al.^[16] constructed FE models and verified that proximal femoral tunnel malposition impairs lateral patellar restraint. However, existing research has two prominent drawbacks: most FE studies rely on patient-specific models with heavy modeling workloads, and few reports combine biomechanical simulation with longitudinal clinical follow-up to correlate tunnel offset with patient functional outcomes. The present study established a standardized idealized FE model to eliminate inter-individual anatomical confounders, combined with a 34-patient clinical cohort, to construct a complete logical chain: tunnel deviation → patellofemoral biomechanics → mid-term knee function, providing translational evidence to support FVFI clinical application.

2 Materials and Methods

2.1 Study Design

A mixed research design integrating idealized finite element biomechanical simulation and single-center retrospective clinical cohort analysis was adopted. The FE arm compared patellofemoral mechanical metrics between FVFI and TPFI; the clinical arm enrolled consecutive patients receiving FVFI-MPFL reconstruction to analyze the correlation between 3D femoral tunnel deviation and 6-month postoperative outcomes. This trial was approved by the Institutional Ethics Committee (Approval No.: 2024-LLPJ-012).

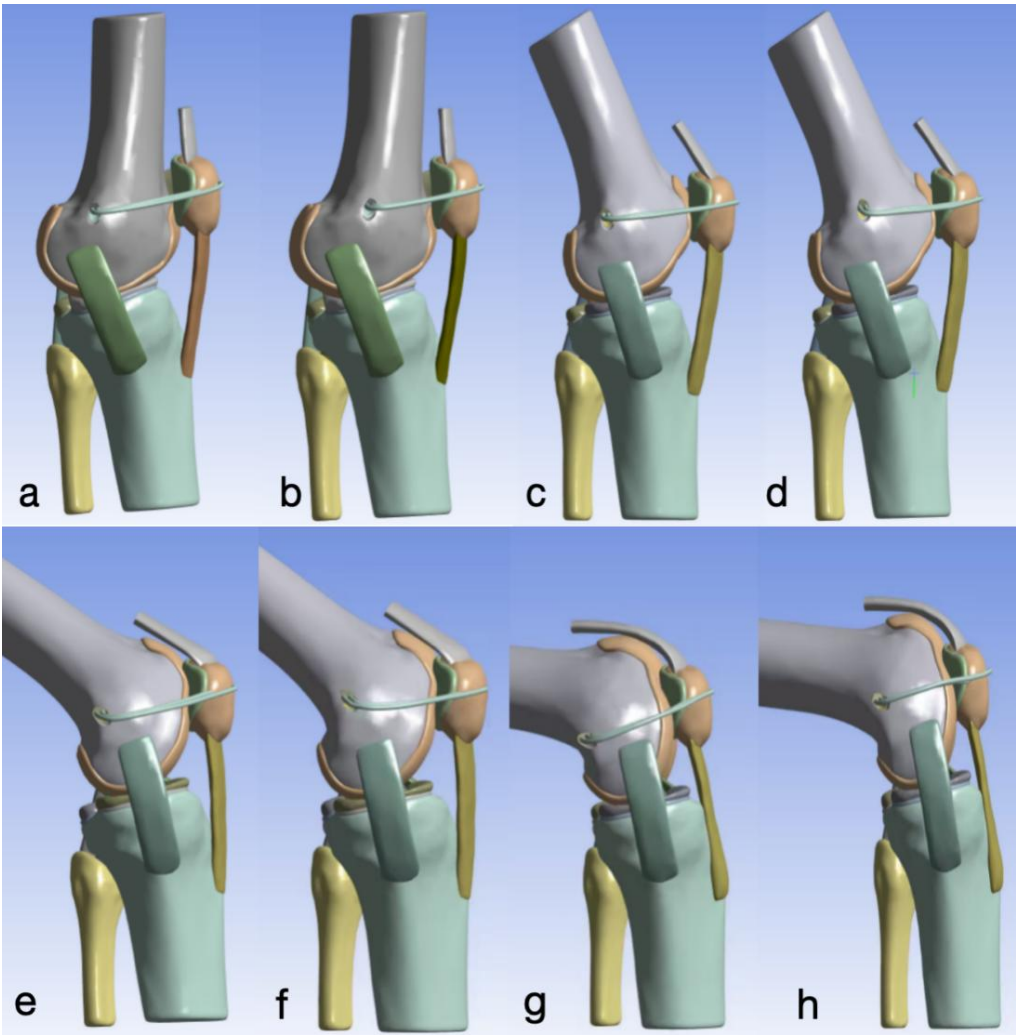
2.2 Construction of idealized finite element model

2.2.1 Model reconstruction and meshing

One patient with ideal knee anatomy (Dejour type A trochlear dysplasia, Insall-Salvati ratio 0.8–1.2, no patellar tilt/tracking disorder) was selected from the clinical cohort. Slice thickness of knee CT images was 1 mm. CT data were imported into Mimics 21.0 for 3D segmentation of femur, patella and articular cartilage, exported as STL mesh files. STL models were processed in Geomagic Wrap 2021 to repair holes, remove burrs and eliminate non-manifold edges, generating watertight NURBS solid models exported as STEP format. STEP assemblies were imported into

SOLIDWORKS 2024 for anatomical alignment, and parametric femoral tunnels and MPFL grafts were created for FVFI and TPFI groups separately. Mesh partitioning was performed in ANSYS 2021 R2: cortical/cancellous bone adopted Solid187 tetrahedral elements (global mesh size 2–3 mm, contact surface refinement to 1.5 mm); MPFL graft adopted Beam188 beam elements (diameter 4 mm, mesh size 2 mm). Mesh quality criteria: element aspect ratio < 5, skewness coefficient < 0.7 (Figure 1).

Figure 1 3D finite element assemblies of two MPFL reconstruction models



Notes: a FVFI 0°; b TPFI 0°; c FVFI 30°; d TPFI 30°; e FVFI 60°; f TPFI 60°; g FVFI 90°; h TPFI 90°

2.2.2 Material properties and boundary conditions

Material mechanical parameters referenced standardized values from peer-reviewed orthopaedic FE studies^[5,17–20], summarized in Table 1.

Table 1 Material mechanical parameters used in finite element simulation

Tissue structure	Elastic modulus (MPa)	Poisson's ratio
Cortical bone	17000	0.30
Cancellous bone	350	0.25
Articular cartilage	20	0.46
MPFL graft	300	0.30
Quadriceps/patellar tendon	2000	0.30
Meniscus	59	0.49
ACL	1.046	0.40
PCL	1.035	0.40
MCL	1.063	0.40
LCL	1.063	0.40
Interference screw	4100	0.30

Boundary constraints and loading settings:

Distal tibia fully fixed; femur allowed sagittal rotation from 0° to 90°, patella free in six degrees of freedom;

Quadriceps tensile load: 200 N (0°), 400 N (30°), 600 N (60°), 800 N (90°)^[5,22];

Graft pre-tension: 5 N at full knee extension to simulate intraoperative physiological tension.

2.3 Biomechanical simulation protocol

Two FE assemblies with identical anatomical/mesh/loading parameters, differing only in femoral tunnel center position:

FVFI group: Tunnel centered at native MPFL femoral footprint, diameter 4.5 mm, 45°

relative to femoral long axis;

TPFI group: Tunnel centered at classic Schöttle radiographic landmark.

2.4 Clinical cohort methodology

2.4.1 Inclusion and exclusion criteria

Inclusion criteria: Clinical diagnosis of recurrent patellar dislocation (≥ 2 documented dislocation episodes); Age < 30 years old; Tibial tuberosity-trochlear groove (TT-TG) distance < 20 mm; Complete pre- and postoperative knee CT data available; Minimum 6-month clinical follow-up; Isolated MPFL reconstruction combined with lateral retinacular release only.

Exclusion criteria: Outerbridge grade $\geq$ III chondral injury; Prior knee surgical history; Severe Dejour type D trochlear dysplasia; High patella (Insall-Salvati ratio > 1.2).

2.4.2 Baseline patient characteristics

34 consecutive eligible patients treated between Jan 2024 and Oct 2025 were stratified by postoperative 3D CT-measured 3D Euclidean distance between actual tunnel center and ideal FVFI anatomical landmark:

Precise positioning group (PPG): Deviation ≤ 3 mm, $n = 28$

General positioning group (GPG): Deviation > 3 mm, $n = 6$

Baseline variables collected: continuous data (age, BMI, preoperative dislocation count, Insall-Salvati ratio, Beighton score); categorical data (gender); ordinal data (Dejour trochlear classification).

2.4.3 Standard FVFI surgical technique

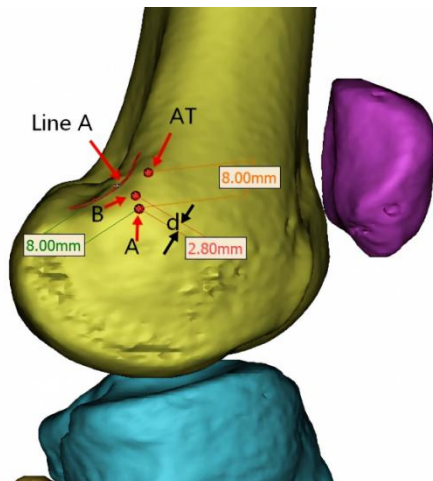
Medial femoral and auxiliary arthroscopic portals were created; synovium over the medial femoral condyle was debrided, and deep fascia released with radiofrequency ablation to fully expose the adductor tubercle and native MPFL footprint. The ideal tunnel landmark was marked 8 mm distal and 8 mm posterior to the apex of the adductor tubercle. A 4.5-mm drill was used to create the femoral tunnel; autologous gracilis tendon graft was fixed with interference screws. Intraoperative knee flexion from 0° to 110° verified graft isometry with length change controlled ≤ 2 mm^[6].

2.4.4 Measurement of femoral tunnel deviation

Postoperative CT scans (slice thickness 1.0 mm) were imported into Mimics software

to calculate the 3D linear offset between the actual tunnel center and native FVFI anatomical landmark for group stratification.(Figure 2)

Figure 2 3D CT measurement diagram of femoral tunnel three-dimensional deviation after MPFL reconstruction



AT indicates the adductor tubercle. Point A represents the optimal native femoral footprint of the MPFL, located 8 mm distal to the apex of the adductor tubercle and 8 mm anterior to the posterior femoral cortex (Line A). Point B denotes the actual intraoperative femoral tunnel position. The parameter d shows the three-dimensional Euclidean distance between the actual tunnel position (Point B) and the optimal anatomical landmark (Point A).

2.5 Clinical outcome measures

Primary outcomes: Knee ROM, Kujala score, Lysholm score at 1, 3 and 6 months postoperatively.

Secondary outcomes: Postoperative patellar redislocation rate, 6-month patient satisfaction score.

2.6 Statistical analysis

All statistical analyses were performed using SPSS 26.0; two-tailed $\alpha = 0.05$ was defined as the significance threshold.

Baseline data: Shapiro-Wilk test for normality. Non-normal continuous variables were described as median (interquartile range) and compared via Mann-Whitney U test; normally distributed continuous variables were expressed as mean $\pm$ standard deviation and compared via independent samples t-test. Categorical gender data with expected frequencies < 5 used Fisher's exact test; ordinal Dejour classification was analyzed by Mann-Whitney U test.

Finite element data: Descriptive statistics only, as no repeated FE specimens were generated.

Postoperative repeated measures: ROM, Kujala and Lysholm scores were analyzed via repeated-measures ANCOVA with preoperative dislocation times as a covariate. Mauchly's sphericity test was performed; Greenhouse-Geisser correction was applied if sphericity was violated. Postoperative redislocation was analyzed by Fisher's exact test. Six-month satisfaction exhibited non-normal distribution and was compared using Mann-Whitney U test.

3 Results

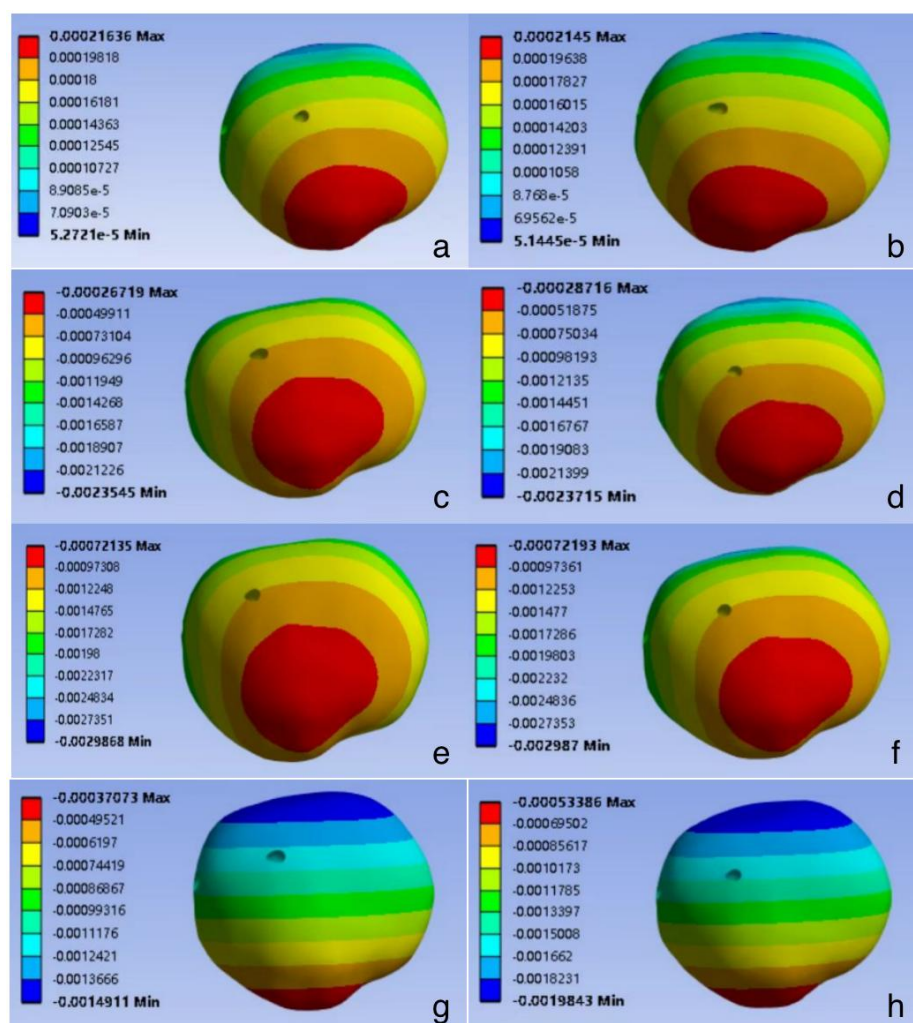
3.1 Finite element biomechanical outcomes

3.1.1 Patellar lateral translation

At 0°, 30°, 60°, 90° flexion, lateral patellar translation (mm) was FVFI: 0.22, -0.27, -0.72, -0.37; TPFI: 0.21, -0.29, -0.72, -0.53 (+ = medial shift, - = lateral shift).

Translation magnitude was comparable at 0°/30°/60°, while TPFI exhibited greater lateral patellar shift at 90°. The absolute translation value of both groups was consistently < 1.0 mm, falling within the physiological stability range reported in cadaveric studies (Figure 3, Table 2).

Figure 3 Contour nephograms of patellar lateral translation at four knee flexion angles



Notes: a FVFI 0°; b TPFI 0°; c FVFI 30°; d TPFI 30°; e FVFI 60°; f TPFI 60°; g FVFI 90°; h TPFI 90°

Table 2 Mean patellar lateral translation (mm) across flexion angles

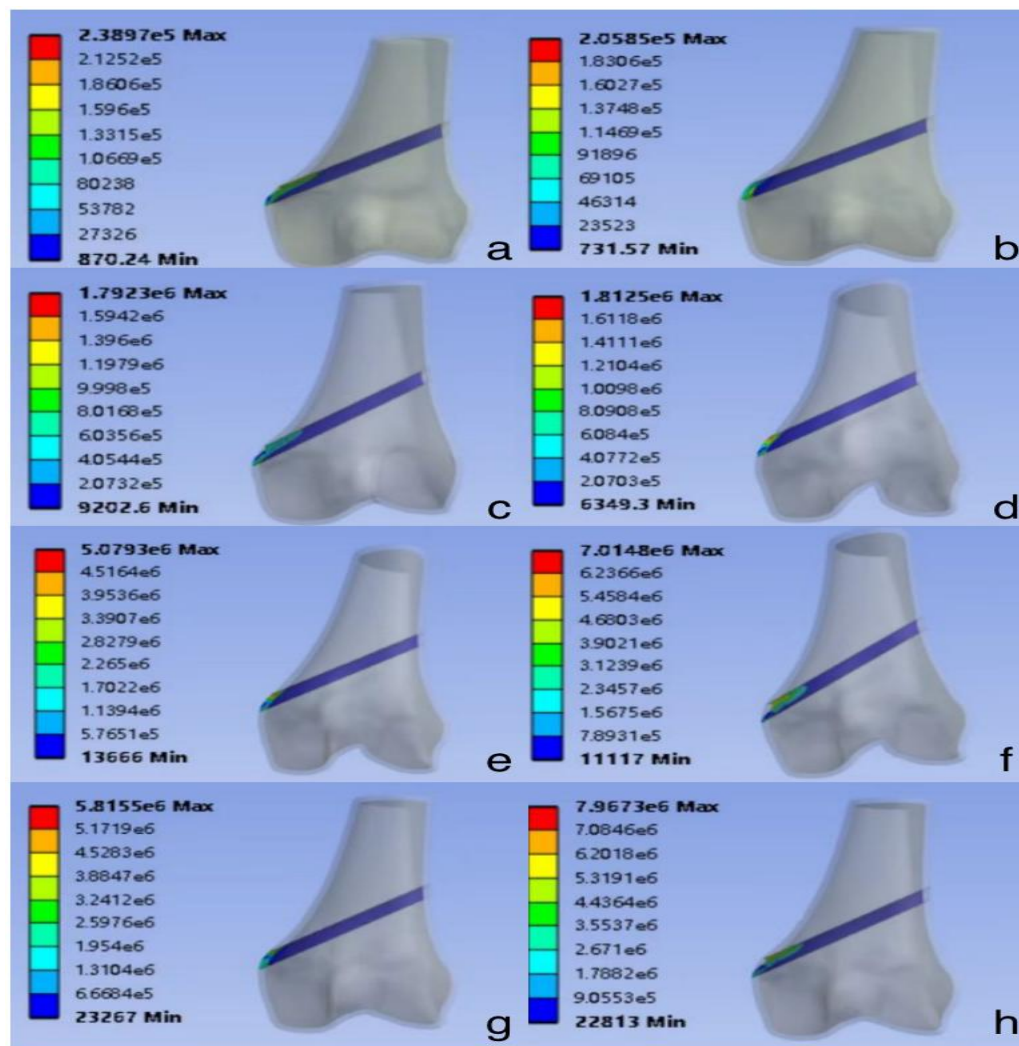
	0°	30°	60°	90°
FVFI	0.22	-0.27	-0.72	-0.37
TPFI	0.21	-0.29	-0.72	-0.53

Note: "+" indicates the displacement direction is towards the medial side of the patella; "-" indicates the displacement direction is towards the lateral side of the patella.

3.1.2 Peak femoral tunnel stress

FVFI peak tunnel stress (MPa): 0.24 (0°), 1.79 (30°), 5.08 (60°), 5.82 (90°); TPFI: 0.21 (0°), 1.81 (30°), 7.01 (60°), 7.97 (90°). Tunnel stress was nearly identical at low flexion, while TPFI generated substantially higher stress at 60° and 90° deep flexion (Figure 4, Table 3).

Figure 4 Contour nephograms of femoral tunnel peak stress



Notes: a FVFI 0°; b TPFI 0°; c FVFI 30°; d TPFI 30°; e FVFI 60°; f TPFI 60°; g FVFI 90°; h TPFI 90°

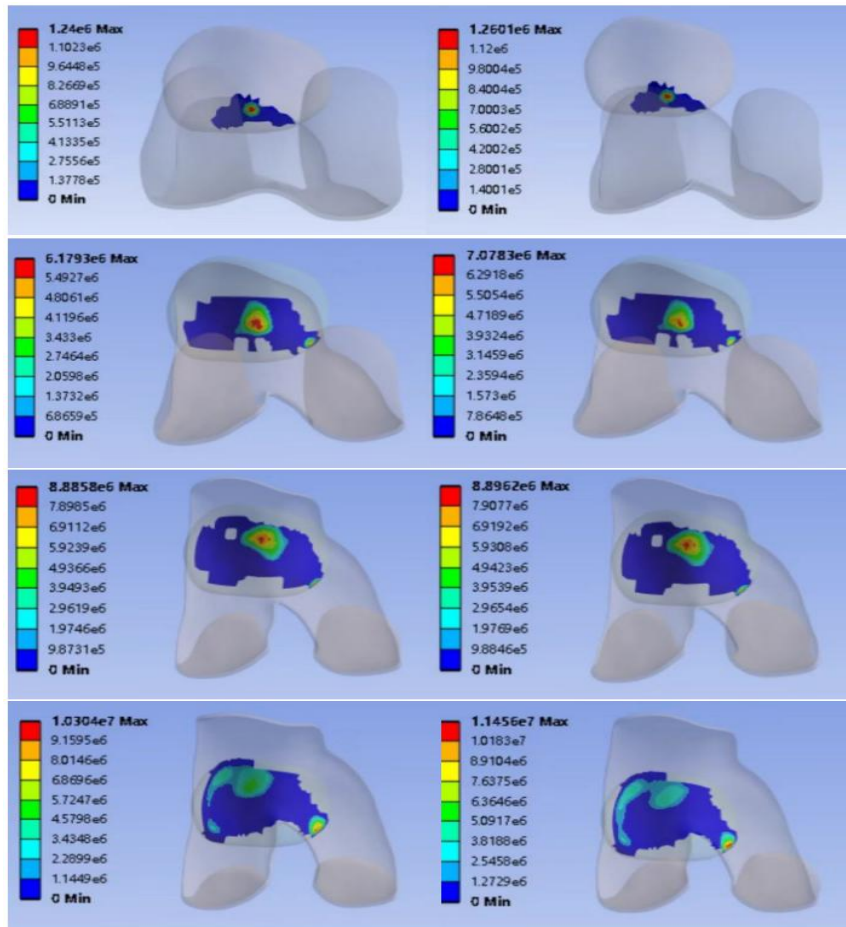
Table 3 Peak femoral tunnel stress (MPa) at different flexion angles

	0°	30°	60°	90°
FVFI	0.24	1.79	5.08	5.82
TPFI	0.21	1.81	7.01	7.97

3.1.3 Average patellofemoral contact pressure

Average contact pressure (MPa): FVFI 0.058 (0°), 0.450 (30°), 0.590 (60°), 0.786 (90°); TPFI 0.059 (0°), 0.457 (30°), 0.591 (60°), 0.790 (90°). Minimal intergroup differences were detected across all flexion positions (Figure 5, Table 4).

Figure 5 Patellofemoral contact pressure distribution nephograms



Notes: a FVFI 0°; b TPFI 0°; c FVFI 30°; d TPFI 30°; e FVFI 60°; f TPFI 60°; g FVFI 90°; h TPFI 90°

Table 4 Mean patellofemoral contact pressure (MPa)

	0°	30°	60°	90°
FVFI	0.058	0.450	0.590	0.786
TPFI	0.059	0.457	0.591	0.790

3.2 Baseline demographic comparison

Baseline data are summarized in Table 5. Age, BMI, Insall-Salvati ratio, Beighton score, gender and Dejour classification showed no significant intergroup differences (all $P > 0.05$). Only preoperative dislocation times were significantly higher in the precise group ($Z = -2.201$, $P = 0.033$). Repeated-measures ANCOVA was therefore applied to adjust for this baseline confounder.

Table 5 Baseline characteristics of two patient cohorts

Variable	Precise group (n=28)	General group (n=6)	Statistic	P-value
Age (y), <i>M</i> (<i>P</i> 25, <i>P</i> 75)	16.5 (14,19)	16.0 (14,21)	<i>Z</i> = -0.137	0.912 ^a
BMI (kg/m ²), <i>M</i> (<i>P</i> 25, <i>P</i> 75)	21.00 (18.04,23.61)	20.50 (15.00,37.00)	<i>Z</i> = -0.091	0.947 ^a
Insall-Salvati ratio, <i>x</i> ̄±s	1.31 ± 0.20	1.25 ± 0.13	<i>t</i> = 0.756	0.455 ^b
Preoperative dislocations, <i>M</i> (<i>P</i> 25, <i>P</i> 75)	2 (1,3)	1 (1,2)	<i>Z</i> = -2.201	0.033 ^a
Beighton score, <i>x</i> ̄±s	5.07 ± 1.84	4.83 ± 2.48	<i>t</i> = 0.270	0.789 ^b
Gender (male/female)	4/24	1/5	–	1.000 ^c
Dejour type (A/B/C)	7/16/5	1/5/0	<i>Z</i> = -0.287	0.809 ^a

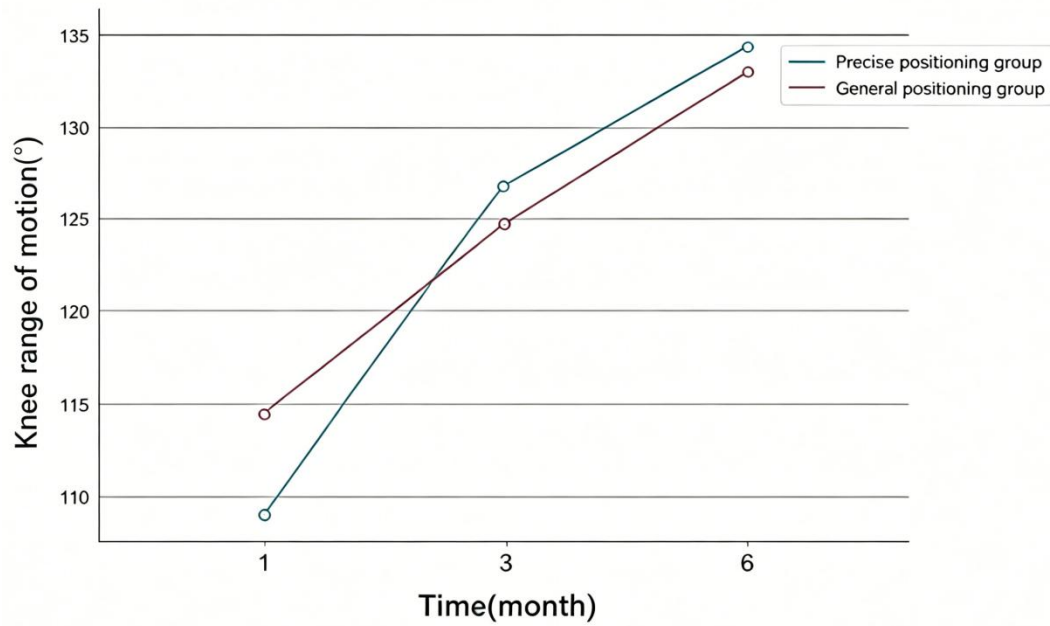
a :Mann-Whitney U test; b :Independent samples t-test; c :Fisher's exact test

3.3 Clinical follow-up outcomes

3.3.1 Knee ROM

ROM at 1/3/6 months: Precise group (109.29±9.40)°, (126.79±5.13)°, (134.46±2.49)°; General group (113.33±6.83)°, (125.00±4.47)°, (133.33±2.58)°. Mauchly's sphericity test *P*<0.001, Greenhouse-Geisser ϵ = 0.678. Time main effect *F* = 68.162, *P*<0.001 (significant ROM improvement over time). Intergroup main effect *F* = 0.083, *P* = 0.775; interaction *F* = 3.226, *P* = 0.067, no significant group differences in ROM progression. Covariate effect of preoperative dislocations *F* = 0.128, *P* = 0.723 (no independent confounding influence).Figure 6.

Figure 6 Knee range of motion follow-up line graph



3.3.2 Kujala score

Kujala scores at all follow-up timepoints were significantly higher in the precise group. Sphericity test $P = 0.804$, no correction required. Time effect $F = 211.621$, $P < 0.001$; intergroup $F = 10.917$, $P = 0.002$; interaction $F = 1.661$, $P = 0.198$. Spearman correlation showed tunnel deviation was moderately negatively correlated with 6-month Kujala score ($r_s = -0.339$, $P = 0.050$). Patients were divided into two groups according to the femoral tunnel deviation threshold of 3 mm. The Mann-Whitney U test demonstrated significantly lower 6-month Kujala scores in patients with deviation > 3 mm compared with those with deviation ≤ 3 mm. Figure 7, Figure 8, Figure 9.

Figure 7 Kujala score follow-up line graph

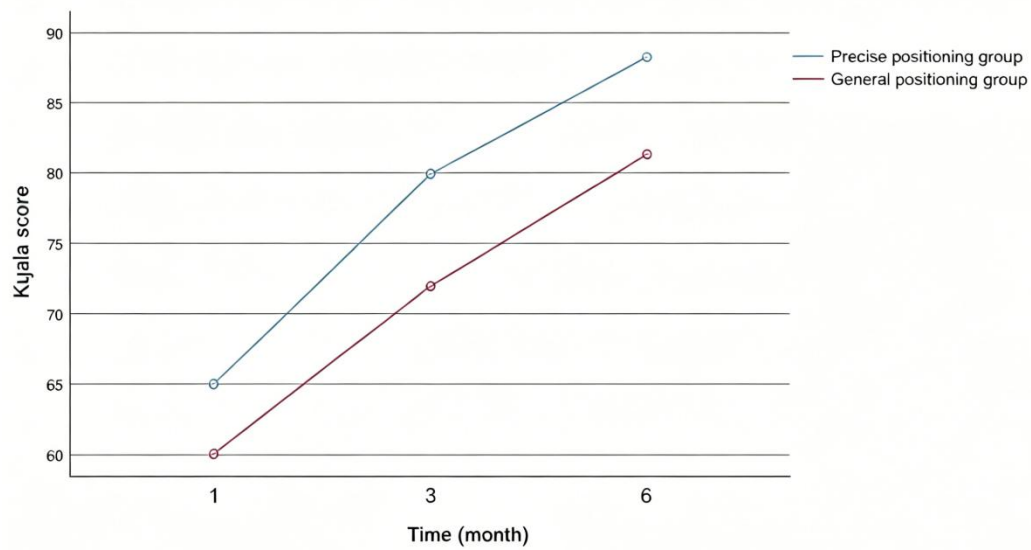


Figure 8 Scatter plot showing Spearman correlation between femoral tunnel 3D deviation and 6-month Kujala score

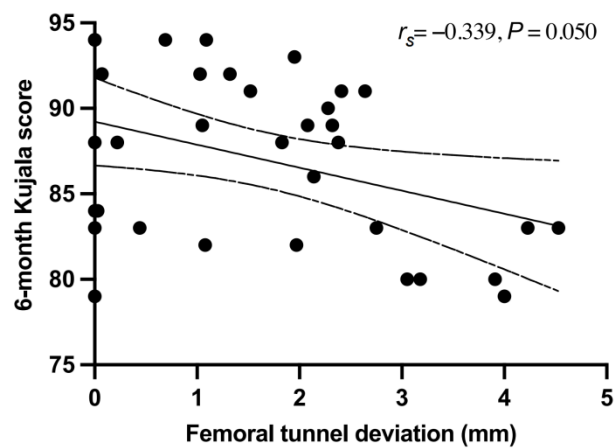


Figure8. Scatter plot showing the association between femoral tunnel deviation and 6-month postoperative Kujala score. A linear regression line and corresponding 95% confidence band were added for visual trend demonstration. Spearman's rank correlation test was used for statistical analysis ($r_s = -0.339, P = 0.050$).

Figure9

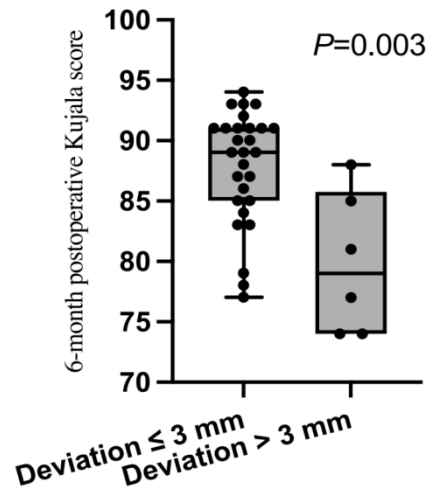
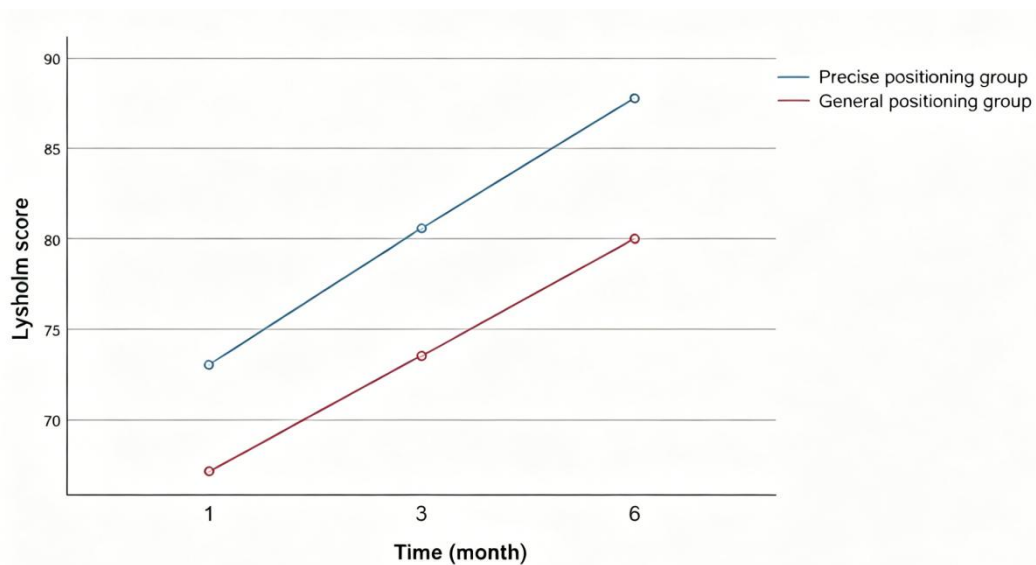


Figure9 Box-and-whisker plot overlaid with individual data points comparing 6-month postoperative Kujala scores between patients with femoral tunnel deviation ≤ 3 mm ($n = 28$) and those with deviation > 3 mm ($n = 6$). Intergroup comparison was conducted using the Mann-Whitney U test. $P < 0.05$.

3.3.3 Lysholm score

Lysholm scores were consistently superior in the precise group. Sphericity test $P = 0.074$. Time main effect $F = 89.072$, $P < 0.001$; intergroup effect $F = 11.011$, $P = 0.002$; interaction $F = 0.786$, $P = 0.460$. Covariate preoperative dislocation count exerted no independent impact ($F = 0.108$, $P = 0.745$).Figure 10.

Figure 10 Lysholm score follow-up line graph



3.3.4 Redislocation rate

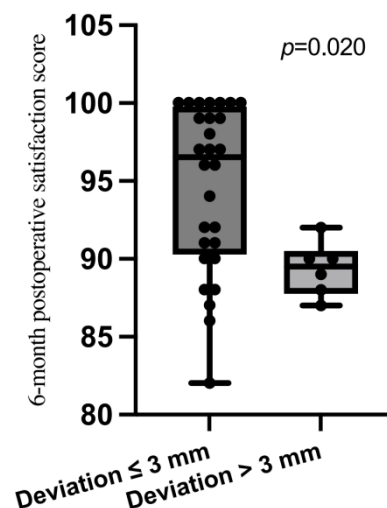
Precise group redislocation: 1/28 (3.57%); General group: 1/6 (16.67%). Fisher's

exact test $P > 0.05$, no statistical difference.

3.3.5 Six-month patient satisfaction

Overall satisfaction score: 93.7 ± 5.24 (range 82–100). Mann-Whitney U test $U = 33.500$, $Z = -2.296$, $P = 0.020$, precise group satisfaction significantly higher. Figure 11.

Figure 11 Two groups of 6-month satisfaction box plots



3.4 Outcome summary

Both precise group and general group surgery significantly improved knee ROM, Kujala and Lysholm scores over the 6-month follow-up period. After covariate adjustment, ROM and redislocation rates were comparable between groups; patients with tunnel deviation ≤ 3 mm achieved superior functional scores and subjective satisfaction. Non-significant group-time interaction indicated identical recovery velocity, with functional gaps maintained from early to mid-term follow-up. Preoperative dislocation times had no independent effect on repeated functional endpoints, confirming effective confounder correction via ANCOVA. (Table 6)

Table 6 Follow-up score summary table

Outcome measure	Follow-up time	Precise positioning group (n = 28)	General positioning group (n = 6)
Knee ROM (°)	1 month	109.3 ± 9.4	113.3 ± 6.8
	3 months	126.8 ± 5.1	125.0 ± 4.5

Outcome measure	Follow-up time	Precise positioning group (n = 28)	General positioning group (n = 6)
Kujala score	6 months	134.5 ± 2.5	133.3 ± 2.6
	1 month	65.1 ± 4.5	59.5 ± 5.5
	3 months	80.0 ± 5.2	71.3 ± 3.1
Lysholm score	6 months	88.3 ± 4.4	80.8 ± 1.7
	1 month	73.1 ± 3.6	67.0 ± 4.8
	3 months	80.8 ± 4.8	73.3 ± 7.7
	6 months	87.9 ± 4.7	79.8 ± 5.9

Note. ROM, range of motion; SD, standard deviation. Repeated-measures analysis of variance (ANOVA) was performed to evaluate intergroup effects, time effects, and group × time interaction effects. $P < 0.05$ was considered statistically significant. Intergroup effect: Kujala score ($F = 10.917$, $P = 0.002$); Lysholm score ($F = 11.011$, $P = 0.002$); knee ROM ($F = 0.083$, $P = 0.775$). Time effect: All three functional outcomes improved significantly over time (all $P < 0.001$). Group × time interaction effect: Kujala score ($F = 1.661$, $P = 0.198$); Lysholm score ($F = 0.786$, $P = 0.460$); knee ROM ($F = 3.226$, $P = 0.067$). No significant interaction was detected for any outcome.

4 Discussion

4.1 Biomechanical comparison of two femoral tunnel positioning techniques

Lateral patellar translation represents the most intuitive indicator for evaluating lateral patellar stability^[21]. Under knee flexion angles of 0°, 30° and 60°, lateral patellar translation was comparable between the FVFI and TPFI groups. Only at deep flexion of 90° was a slight increase in lateral patellar displacement observed in the TPFI group. Although the Schöttle point serves as a radiographic surrogate landmark, it lies anatomically close to the native MPFL femoral footprint. Provided no substantial offset occurs, both positioning techniques can effectively restore the lateral restraining function of the MPFL, preserve normal patellar kinematics, and maintain fundamental knee joint stability.

Mean patellofemoral contact pressure is closely associated with postoperative cartilage degeneration and joint pain. Over the full flexion range from 0° to 90°, inter-group differences in average patellofemoral contact pressure were minimal. Previous biomechanical investigations have demonstrated that postoperative patellofemoral pressure is predominantly governed by graft pre-tension and patellar tunnel position. Given moderate femoral tunnel offset, the influence of femoral positioning approaches on joint contact pressure remains limited^[6]. With a uniform 5 N graft pre-tension and standardized patellar tunnel configuration in our model, neither positioning strategy produced abnormally elevated patellofemoral pressure. Biomechanically, both techniques avoid additional risk of articular cartilage wear.

Peak femoral tunnel stress constitutes the key parameter distinguishing the two positioning methods^[22]. At low flexion angles (0° and 30°), tunnel stress was similar in both groups. When the knee was flexed to deep-flexion positions (60° and 90°), however, peak tunnel stress was markedly higher in the TPFI group, with a maximum difference of 2.15 MPa. From an anatomical and mechanical perspective, the native MPFL femoral footprint is located on the medial femoral bony ridge. The FVFI technique aligns graft loading orientation with femoral bony architecture and achieves more homogeneous stress distribution. By contrast, the Schöttle point is biased toward the posterior femoral cortex. During deep knee flexion, graft traction generates shear stress against the femoral cortex and induces local stress concentration within the tunnel. As reported in existing literature^[23], chronically elevated tunnel stress facilitates bone resorption, tunnel widening and graft micromotion--major contributors to long-term surgical failure and functional deterioration. The FVFI method effectively reduces tunnel stress under deep flexion, optimises local mechanical environments, and improves long-term osseointegration stability between graft and bone tunnel.

4.2 Clinical correlation of 3D femoral tunnel deviation

After correcting preoperative dislocation bias, patients with deviation > 3 mm exhibited inferior mid-term Kujala and Lysholm scores without significant ROM impairment.

ROM is primarily determined by soft tissue adhesions and postoperative rehabilitation, minimally affected by femoral tunnel offset. Increased tunnel deviation disrupts graft isometry, inducing recurrent mild pain and giving-way episodes during daily activity, explaining poorer functional outcomes. Although the general group had numerically higher redislocation risk (16.67% vs 3.57%), small sample size (n=6) limited statistical power to detect true differences. According to clinical trends and previous evidence, increased femoral tunnel offset compromises graft restraining capacity and elevates the risk of lateral patellar instability. When offset exceeds 5 mm, graft isometry is substantially destroyed and redislocation risk rises markedly^[24,25]. Patient satisfaction was significantly better in the precise cohort, reflecting reduced chronic discomfort and superior self-reported knee function. Spearman correlation validated the complete causal chain: increased tunnel offset → abnormal patellofemoral kinematics → impaired clinical function.

4.3 Clinical significance of the 3-mm deviation tolerance threshold

The native MPFL femoral footprint forms an elliptical bony ridge with inherent dimensional tolerance. A 3-mm 3D offset still lies within the anatomical footprint and preserves native graft biomechanics; deviation exceeding this boundary alters graft force transmission and impairs mid-term function. Unlike 2D fluoroscopy-dependent Schöttle positioning prone to projection error^[26], FVFI uses direct arthroscopic anatomical landmarks combined with postoperative 3D CT 3-mm cutoff as standardized intraoperative quality control, lowering the learning curve for junior surgeons and community hospital implementation.

4.4 Comparison with existing domestic and international literature

Most published MPFL-reconstruction studies are limited to either isolated biomechanical experiments or pure clinical follow-up investigations, with few integrating both domains for cross-validation^[27-30]. The mixed-design approach combining FE biomechanical simulation and clinical longitudinal follow-up adopted herein fills this research gap. By simulating two clinically-adopted positioning

techniques, our study confirms that the principal advantage of FVFI lies not in enhanced patellar stability but in reduced tunnel stress under deep flexion, supplementing evidence regarding positioning-related tunnel biomechanics. Moreover, we innovatively stratified patients using the 3-mm cut-off value and established correlations between biomechanical metrics and clinical endpoints. According to long-term follow-up literature^[31], tunnel offset mainly influences early-to-mid-term knee function, whereas long-term patellofemoral osteoarthritis is multifactorial and modulated by age, physical activity and pre-existing chondral status. Our findings complement existing evidence.

4.5 Strengths and limitations

Strengths

Integrated mixed design linking standardized FE biomechanics and real clinical longitudinal data to establish a complete mechanism-outcome chain; First proposed quantitative 3-mm tolerance threshold for FVFI tunnel placement to guide intraoperative quality assurance; Rigorous statistical adjustment for baseline imbalance via repeated-measures ANCOVA; Strict unified inclusion/exclusion criteria minimizing anatomical confounders.

Limitations

Uneven sample size (n=6 general group) reduces statistical power for binary endpoints such as redislocation; Single idealized FE model without anatomical variants (severe trochlear dysplasia, patella alta), limiting generalizability of mechanical data; Only 6-month mid-term follow-up, lacking long-term data on tunnel widening and osteoarthritis progression; Satisfaction scores could not be adjusted for baseline dislocation confounders due to non-normal distribution; Single-center retrospective design carries inherent selection bias.

4.6 Clinical recommendations

Intraoperative target: Prioritize arthroscopic native footprint marking, control 3D tunnel deviation ≤ 3 mm as core quality standard; Schöttle landmark may serve only as secondary reference. Individualized strategy: Strict 3-mm limit for

adolescent/high-demand patients; minor offset within 3 mm acceptable for low-activity elderly patients. Postoperative management: Routine 3D CT to quantify tunnel offset; intensified long-term surveillance for patients with deviation > 3 mm. Technique promotion: FVFI reduces fluoroscopic radiation and possesses robust tolerance, suitable for widespread clinical adoption.

4.7 Future perspectives

Multi-center prospective large-cohort trials with extended 2–5 year follow-up to validate the 3-mm threshold; Patient-specific FE models incorporating various trochlear deformities to analyze offset effects under complex anatomy; Investigate mechanical and clinical consequences of severe offset > 5 mm; Combine 3D printing/robot-assisted navigation to further improve tunnel accuracy; Subgroup analysis stratified by age and activity level for individualized surgical guidance.

5 Conclusion

Full arthroscopic native femoral footprint MPFL reconstruction effectively reduces femoral tunnel peak stress during deep knee flexion while maintaining physiological patellar tracking and patellofemoral contact pressure. When 3D femoral tunnel deviation is limited within 3 mm, patients achieve superior mid-term knee function and patient satisfaction without compromising early stability or knee mobility. The quantitative 3-mm tolerance threshold provides standardized intraoperative quality control criteria, supporting wide clinical promotion of FVFI MPFL reconstruction for recurrent patellar dislocation.

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Declarations

Ethics approval and consent to participate

This retrospective clinical study was approved by the Institutional Ethics Committee of Xining No.1 People's Hospital (Approval No.: 2024-LLPJ-012). The requirement for written informed consent was waived by the ethics committee due to retrospective chart review design. All procedures complied with the Declaration of Helsinki.

Clinical trial number

not applicable.

Consent for publication

Not applicable.

Availability of data and materials

Raw clinical patient datasets cannot be publicly released to protect participant privacy; de-identified data are available from the corresponding author upon reasonable request. Finite element modeling datasets are provided as supplementary materials.

Competing interests

The authors declare no competing financial or non-financial interests.

Funding

This work was supported by the 2025 Key Research and Development & Transformation Project of Xining Science and Technology Bureau, Qinghai Province, under the title Clinical Study of All-Arthroscopic MPFL Reconstruction for Recurrent Patellar Dislocation (Project No. 2025-Y-12).

Authors' contributions

Conceptualization: Lei K, Li CF; Methodology: Lei K, Zeng XZ, Li CF; Software: Lei K, Li CH; Formal analysis: Lei K, Zeng XZ; Data curation: Lei K, Zeng XZ, Li CH; Investigation: Lei K, Li CH; Visualization: Zeng XZ; Funding acquisition: Zeng XZ, Fan C; Project administration: Li CF; Writing-original draft: Lei K; Writing-review & editing: Lei K, Zeng XZ, Li CF; Supervision: Li CF. All authors read and approved the final manuscript.