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Research article

Anatomic femoral tunnel and satisfactory clinical outcomes achieved with the modified transtibial technique in anterior cruciate ligament reconstruction: A systematic review and meta-analysis

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A R T I C L E I N F O

Keywords:
Anterior cruciate ligament
Anatomic reconstruction
transtibial
Clinical outcomes
Tunnel characteristics

A B S T R A C T

Background: Anatomic anterior cruciate ligament (ACL) reconstruction is considered the gold standard treatment for ACL injuries because it aims to restore the knee's normal anatomy and stability, while also protecting long-term knee health. Long-term clinical and radiological outcomes after ACL reconstruction using the modified TT technique are unclear.
Objective: To assess the clinical and radiological outcomes following ACL reconstruction using modified transtibial (TT) techniques at a minimum 12-month follow-up.
Design: A systematic review with meta-analysis.
Methods: PubMed, EMBASE, Web of Science, the Cochrane Library, and MEDLINE databases were searched from the inception to December 1, 2022. PICO search strategy was used to identify studies applying modified TT techniques on patients with ACL reconstruction and a minimum follow-up of 12 months. Eligible studies were identified independently by two reviewers. We extracted data on patient demographics, surgical characteristics, patient reported outcomes including subjective evaluations and clinical outcomes. Radiological data including femoral and tibial tunnel position, femoral and tibial tunnel length, and femoral tunnel angle were also extracted. The tunnel position was evaluated using the quadrant method based on three-dimensional computed tomography (3D CT) images. The standardized mean difference (SMD) and 95 % confidence interval (CI) were calculated for clinical and radiological outcomes.
Results: Sixteen studies involving 628 patients were finally included. The SMD of Lysholm (90.39; 95 % CI 83.41–97.38), IKDC (86.07; 95 % CI 79.84–92.31), and Tegner (6.15; 95 % CI 3.96–8.33) scores were considered satisfactory. The depth of the femoral tunnel showed a pooled SMD of 30.08 % (95 % CI 28.25–31.91 %), and the height showed a pooled SMD of 37.72 % (95 % CI 35.75–39.70 %). The pooled SMD for the femoral tunnel angle in the coronal plane was 48.27° (95 % CI 43.14–53.40°), and the pooled SMD for the femoral tunnel length was 33.98 mm (95 % CI 29.03–38.93 mm).

Abbreviations: ACL, anterior cruciate ligament; AM, anteromedial; CT, computed tomography; IKDC, International Knee Documentation Committee; OR, odd ratios; PRISMA, preferred reporting items for systematic reviews and meta-analyses; RCT, randomized controlled trial; SSD, side-to-side difference; SMD, standardized mean difference; TT, transtibial.

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Conclusions: This investigation has shown that modified TT technique can create an anatomic femoral tunnel and maintain optimal tunnel length and angulation. Most patients had satisfactory subjective outcomes and physical examinations after ACL reconstruction using modified TT technique. This information may assist in guiding expectations of clinicians and patients following ACL reconstruction with modified TT technique.

1. Introduction

Anterior cruciate ligament (ACL) reconstruction is one of the most common sports medicine operations [1]. Proper positioning of femoral and tibial tunnels is critical for improving knee stability and biomechanical performance of the graft [2]. The non-anatomic tunnel positioning leads to residual instability, graft failure and subsequent arthritis [3–5]. The importance of anatomic ACL reconstruction has been emphasized, as clinical outcomes are optimized when grafts are placed in the native ACL insertions [3]. Cadaveric studies have demonstrated improved rotational kinematics of the reconstructed knee when the tibial and femoral tunnels are centralized within their respective footprints [2,6].

Various surgical techniques have been proposed for ACL reconstruction [7,8]. Transtibial (TT) technique is a predominant choice for creating femoral tunnel, which is commonly used in ACL reconstruction [9,10]. With a TT drilling method, the placement of the femoral tunnel is constrained by the tibial tunnel [11]. Studies conducted by Brophy et al. [12] and Pearle et al. [13] demonstrated that the traditional TT technique has an inclination for vertical graft orientation, which was associated with rotational instability and inferior outcomes. Due to these limitations, the anteromedial (AM) portal technique has emerged as a popular alternative to the TT approach [14]. In this method, the femoral drill guide is inserted through the medial portal to eliminate tibial tunnel constraint [14,15]. While enabling anatomical femoral apertures, the AM technique presents new technical challenges and results in less optimal tunnels [15]. This can be attributed to the requirement of knee hyperflexion, leading to difficulty in obtaining a consistent view of the lateral notch wall during surgery [8,15]. Moreover, the AM technique may elevate the risk of damage to the articular cartilage of the medial femoral condyle and posterior cortical breakthrough [7].

Technical modifications to the traditional TT technique, such as adjusting the angles and location of the tibial tunnel [16], varus and internal rotation of the tibia [4], have been applied to create an anatomic femoral tunnel. Modified TT technique may increase the obliquity of the femoral tunnel toward an anatomic placement [4,16]. The previous work has shown that a more proximal and medial tibial starting point and the tibial tunnel angle lower than 60° would allow an anatomic single-bundle TT ACL reconstruction [2,17,18]. Some clinical studies have documented the clinical and radiological outcomes comparing the modified TT and AM portal techniques [19–22]. However, controversial findings have been reported in terms of clinical and radiological outcomes, and therefore, long-term outcomes after ACL reconstruction using the modified TT technique are still unclear.

Therefore, the purposes of this study were to conduct a systematic review of the modified TT technique for anatomic ACL reconstruction and to evaluate clinical and radiological outcomes at a minimum 12-month follow-up. Based on previous publications [20–22], we hypothesized that the modified TT technique would create an anatomic femoral tunnel position and provide satisfactory self-reported knee function and improved knee stability.

2. Materials and methods

2.1. Literature search strategy

This review design followed the guidelines established in the PRISMA (Preferred Reporting Items for Systematic Reviews and Meta-Analyses) statement [23]. The literature search was performed through PubMed, EMBASE, Web of Science, the Cochrane Library, and MEDLINE databases from inception to December 1, 2022. Only studies published in English were included. Clinical studies evaluating radiological results and clinical outcomes in patients who underwent modified TT ACL reconstruction were included. Citations of the retrieved articles were manually searched to identify relevant studies potentially missed by the electronic search. The search terms used in the study were as follows: (transtibial OR *trans*-tibial OR conventional) AND (anterior cruciate ligament OR ACL) AND (ACL reconstruction) AND (anatomical OR anatomy).

2.2. Inclusion and exclusion criteria

The inclusion and exclusion criteria were defined before the original search. Inclusion criteria were as follows: (1) a clinical study of human subjects undergoing SB ACL reconstruction with the modified TT technique; (2) an analysis of clinical outcomes and/or radiological results; (3) full reporting of outcomes including sample numbers, means, and standard deviations; (4) the use of appropriate statistical methods; (5) studies with a minimum follow-up period of 12 months. Exclusion criteria were as follows: (1) studies without clinical or radiological outcomes; (2) only cadaveric results included; (3) surgical techniques that did not use TT femoral drilling; (4) studies that included ACL injury with medial collateral ligament, lateral collateral ligament or posterior cruciate ligament injuries; (5) reviews, export opinions, editorial comments, and case series; (6) non-English language articles.

2.3. Literature selection

All potential studies were imported into Endnote X8 (Clarivate), and duplicates were removed. All titles and abstracts were reviewed by two independent authors (Z.L. and L.Y.) and assessed based on the above criteria. If the abstract did not provide sufficient data to determine selection, the full text was then evaluated before final inclusion in this review. Disagreements were resolved by a consensus or by the discussion with the senior author (W.S.B). The protocol for this review was registered on PROSPERO (CRD42022334103). The results of this literature review were outlined in the PRISMA diagram in Fig. 1.

2.4. Data extraction

Data were then extracted from each study by 2 independent investigators using a predefined sheet created by the authors at the onset of the review. Extracted data included first author, publication year, study design, level of evidence, sample size, patient demographics, graft preparation methods, surgical technicalities, clinical outcomes including subjective evaluations (2000 International Knee Documentation Committee [IKDC] subjective knee score, Tegner activity scale, and Lysholm knee score), and objective evaluations (pivot-shift test, Lachman test, anterior drawer test, KT-1000 arthrometer measurement, and IKDC knee examination). The percentage of patients with knees classified as category A or B in the IKDC knee examination was calculated. The side-to-side difference (SSD) of anterior translation was measured with the use of a KT-1000 arthrometer at 30 lb (133 N) with the knee positioned at 20° of flexion.

Radiological data included femoral and tibial tunnel position, femoral and tibial tunnel length, and femoral tunnel angle. Three-dimensional computed tomography (3D CT) images were created and aligned with the femoral and tibial tunnels. The femoral tunnel position was analyzed according to the quadrant method by Bernard et al. [24] using PACS View. The central point of the femoral tunnel coordinates was expressed as a percentage (%) of the dimension in the quadrant in the posterior to anterior direction (parallel to the Blumensaat line) and from the proximal to distal direction (perpendicular to the Blumensaat line). The tibial tunnel position was also analyzed in 3D CT model [25]. The location of the center of the tibial tunnel aperture was measured as a percentage of the total medial-to-lateral and anterior-to-posterior dimensions of the tibial plateau. The lengths of the femoral and tibial tunnels were determined using 3D CT imaging, where the measurement involved quantifying the distance between the center of the tunnel's inner and outer apertures. The obliquity of the femoral tunnels was defined as the angle between the reamed femoral tunnel and femoral condyle tangent line in the coronal plane [26]. In studies that compared the modified TT technique and other drilling techniques (ie,

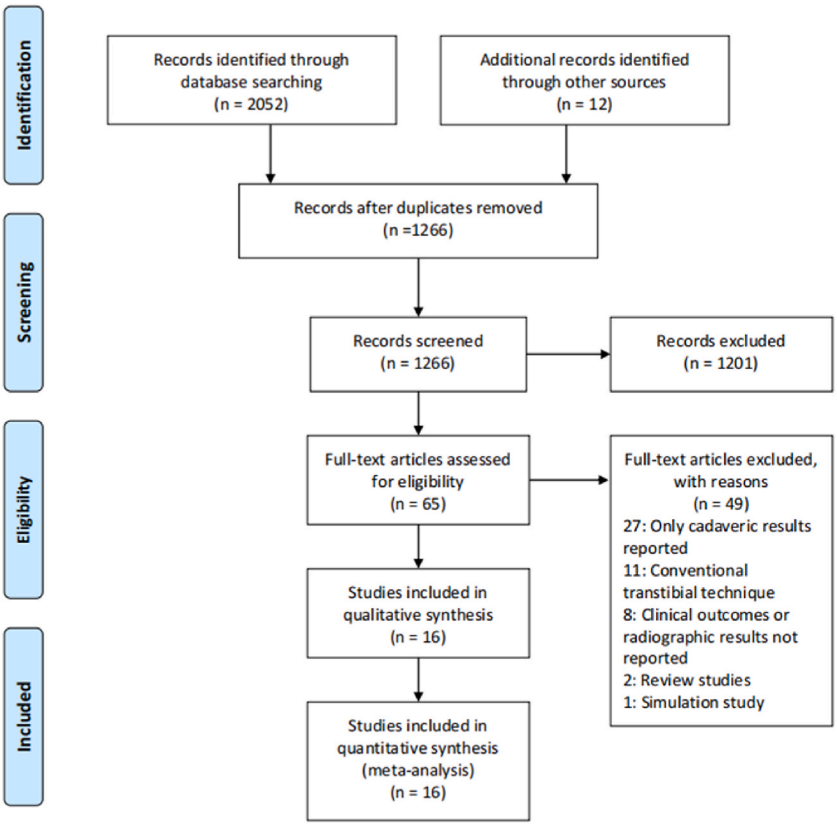

Fig. 1. Flowchart of literature review.

Table 1
Methodological quality of the included studies.

Study (Year)	Randomized adequately[a]	Allocation concealed	Patient blinded	Care provider blinded	Outcome assessor blinded	Acceptable dropout rate[b]	ITT analysis[c]	Avoided selective reporting	Similar baseline	Similar or avoided cofactor	Patient compliance[d]	Similar timing	Overall Quality[e]
Yoon (2014)	Yes	Yes	Unsure	Unsure	Yes	Yes	No	Yes	Yes	Yes	Yes	Yes	High
Sinha (2015)	No	No	No	No	Yes	Yes	No	Yes	Yes	Yes	Yes	Yes	Moderate
Nha (2015)	No	No	No	No	No	Unsure	No	Yes	Yes	Yes	Yes	Yes	Moderate
Vijayan (2021)	No	No	No	No	Yes	Yes	No	Yes	Yes	Yes	Yes	Yes	Moderate
Youm (2013)	No	No	No	No	Unsure	Yes	No	Yes	Yes	Yes	Unsure	Yes	Moderate
Trofa (2020)	Yes	Yes	No	No	Yes	Yes	No	Yes	Yes	Yes	Unsure	Yes	High
Lee(2013)	No	No	No	No	No	Yes	No	Yes	Yes	Yes	No	Yes	Moderate
Lee(2014)	No	No	No	Unsure	No	Yes	No	Yes	Yes	Yes	Yes	Yes	Moderate
Lee (2018)	No	No	No	Unsure	Yes	Yes	No	Yes	Yes	Yes	Yes	Yes	Moderate
Jarvis (2021)	No	No	No	No	Yes	Yes	No	Yes	Yes	Yes	Yes	Yes	Moderate
da Silva (2017)	No	No	No	No	Unsure	Yes	No	Yes	Yes	Yes	Unsure	Yes	Moderate
Chang (2011)	No	No	No	No	Yes	Yes	No	Yes	Yes	Yes	Yes	Yes	Moderate
Silva (2010)	No	No	No	No	Unsure	Yes	No	Yes	Yes	Yes	Yes	Yes	Moderate
Hussin (2018)	Yes	Yes	Yes	No	Yes	Yes	No	Yes	Yes	Yes	Yes	Yes	High
Han (2019)	No	No	No	No	Yes	Yes	No	Yes	Yes	Yes	Yes	Yes	Moderate
Yu (2021)	No	No	No	No	No	Yes	No	Yes	Yes	Yes	Yes	Yes	Moderate

ITT, intention to treat; Mod, moderate.
[a] “Yes” response indicates only if the method of sequence made was explicitly introduced.
[b] “Yes” response indicates dropout rate <20 %.
[c] “Yes” response indicates all randomized participants were analyzed in the group they were allocated to.
[d] “Yes” response indicates intermittent therapy or treatment duration >6 months.
[e] High = “yes” responses on >7 items; moderate = “yes” responses on >4 but ≤ 7 items; low = “yes” response on ≤ 4 items.

Table 2
Study characteristics.

Lead author (Year)	Study design	Level of evidence	Sample size	Mean age (years)	Sex, male: female, n	Graft type	Source	Measured parameters			
								Surgical technicalities	Clinical outcomes	Radiographic results	Mean follow-up period (months)
Yoon (2014)	Prospective randomized	I	20	29.7	20:0	Fresh-frozen achilles tendon	Allograft	The tibial entrance point was anterior to the medial collateral ligament and proximal to the pes anserinus. The angle on the coronal plane between the tibial long axis and the guide wire was about 30–40. With the modified transtibial technique, the knee was flexed to about 80 to avoid posterior cutoff when creating the femoral tunnel. Varus and internal rotation of the tibia made it possible to easily adjust the guide wire at the femoral tunnel marking centrally between the AM and PL footprints.	Subjective evaluations: IKDC, Lysholm score, Tegner activity scale; Objective evaluations: Lachman test, pivot shift test, IKDC knee examination, KT-1000 arthrometer.	3D-CT: the obliquity of the femoral tunnel, the length of the femoral tunnel.	24
Sinha (2015)	Prospective cohort	II	30	27.7	29:1	Semitendinosus-gracilis tendon	Autologous	Tibial guide is set at 50° and placed at the tibial footprint of ACL and lateral to medial tibial spine. The tibial guide was inclined to about 60° to tibial joint line in the coronal plane. Through the pilot tibial tunnel, a guide wire was passed into the intercondylar notch as close to the femoral footprint of native ACL as possible.The free hand positioning of the guide wire was done through tibial tunnel that was one size smaller than final intended size.	Subjective evaluations: Lysholm score; Objective measurements: anterior laxity by Rolimeter testing device, manual pivot shift.	X-ray of knee anteroposterior and lateral views: femoral tunnel angle in coronal plane and sagittal location. Intraoperative direct measuring device: the length of the femoral tunnel	27
Nha (2015)	Retrospective cohort	III	55	35.6	36:19	Semitendinosus and gracilis tendon	Autologous	Tibial drill guide is set at 45° from the starting point at the midway between the posterior cortex of the proximal tibia and the medial margin of the tibial tuberosity. The guide pin is inserted through the offset aimer to mark the reference point which is more proximal than the center of the femoral	Subjective evaluations: IKDC, Lysholm score; Objective evaluations: pivot shift test, anterior drawer test, Lachman test, anterior translation on the Telos stress radiography	3D-CT: the femoral tunnel center from the center of the ACL attachment.	14

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Table 2 (*continued*)

Lead author (Year)	Study design	Level of evidence	Sample size	Mean age (years)	Sex, male: female, n	Graft type	Source	Measured parameters			
								Surgical technicalities	Clinical outcomes	Radiographic results	Mean follow-up period (months)
								footprint due to offset hook. The cannulated femoral guide pin is introduced through the tibial tunnel by the freehand technique without a femoral offset aimer and positioned at the previously marked center of the footprint.			
Vijayan (2021)	Retrospective, nonrandomized	III	37	29.1	34:3	Semitendinosus-gracilis quadrupled graft	Autologous	The tibial tunnel was drilled centring over tibial footprint using the tibial zig placed at an angle of 50° in the sagittal plane and 20° in the coronal plane. With the knee in 90° flexion, more anatomical femoral tunnel was created by applying anterior drawer force, varus stress, external rotation of the tibia and external rotation of the femoral offset guide and directing the jig towards the anatomic centre of the ACL footprint.	Subjective evaluations: IKDC, Lysholm score; Objective measurements: anterior drawer, Lachman's, pivot shift, single-legged hop symmetry index, KT-1000 arthrometer measurements.	NA	24
Youm (2013)	Retrospective cohort	III	50	31.9	45:5	A fresh-frozen tibialis tendon	Allograft	The tibial entrance point was anterior to the medial collateral ligament and proximal to the pes anserinus. The angle on the coronal plane between the tibial long axis and the guidewire was about 30–40°. Using varus and internal rotation of the tibia, it was possible to easily adjust the guidewire at the femoral tunnel mark centrally between the AM and PL footprints	NA	3D-CT: the femoral tunnel center from the center of the ACL attachment.	NA
Trofa(2020)	Prospective randomized	I	10	25.4	7:3	NA	NA	With the knee at 90° of flexion, a 7-mm offset femoral drill guide was inserted through a standard medial portal. Once fully seated within the open slot, the drill guide was advanced to the lateral wall of the notch with the tip of the wire positioned as close as	NA	3D-CT: the location of the center of the femoral tunnel, the location of the center of the tibial tunnel, the graft bending angle in the sagittal and coronal planes.	NA

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Table 2 (*continued*)

Lead author (Year)	Study design	Level of evidence	Sample size	Mean age (years)	Sex, male: female, n	Graft type	Source	Measured parameters			
								Surgical technicalities	Clinical outcomes	Radiographic results	Mean follow-up period (months)
								possible to the center of the femoral ACL footprint. The guide wire was then drilled through the distal femur using a standard motorized drill from outside the tibial tunnel. Pathfinder guide to be separated from the wire and withdrawn from the knee via the medial portal.			
Lee(2013)	Prospective cohort	II	98	27.3	81:17	Semitendinosus tendon	Autologous	The starting point of the tibial edge/periphery was superior to the pes anserinus and the anterior margin of medial collateral ligament. The reference point of tibial tunnel is a little posterior region of the ACL footprint. The angle of the ACL guide was set at 47.5°. The guide wire is inserted toward the triangular shaped funnel trough of the femur by free-hand techniques. While the knee is extended gradually, the guide wire is slid into the anatomical footprint in the bony trough.	NA	3D-CT: the location of the center of the femoral tunnel; Radiograph: lateral inclination of the femoral bone tunnel	12
Lee(2014)	Retrospective, nonrandomized	III	52	NA	40:12	Semitendinosus tendon	Autologous	In creating the tibial tunnel, the entry point was set 4–5 cm distal to the joint line, 2–3 cm posteromedial to the tibial tuberosity, and just anterior to the medial collateral ligament. A guide pin was then inserted at an angle of 60° to the tibial plateau with the use of a tibial drill guide aimed midway between the ACL footprints of the AM and PL bundles. In creating the femoral tunnel, we applied an anterior drawer force, a varus force, and an external rotation force to the proximal aspect of the tibia	Subjective evaluations: IKDC, Lysholm score, Tegner activity scale; Objective evaluations: anterior drawer test, Lachman test, pivot shift test, KT-2000 arthrometer.	2D-CT: graft obliquity; 3D-CT: the femoral and tibial tunnel lengths; the femoral and tibial tunnel positions;	24

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Table 2 (*continued*)

Lead author (Year)	Study design	Level of evidence	Sample size	Mean age (years)	Sex, male: female, n	Graft type	Source	Measured parameters			
								Surgical technicalities	Clinical outcomes	Radiographic results	Mean follow-up period (months)
								while externally rotating the guide.			
Lee (2018)	Retrospective, nonrandomized	III	50	28	34:16	Gracilis tendon and semitendinosus tendon	Autologous	An ACL guide was used to create the tibial tunnel at an angle of 47.5°. The guide pin was placed above the pes anserinus and in front of the medial collateral ligament. The guide pin was inserted into the tibial tunnel toward the preformed funnelshaped bone trough with a free-hand technique. Generally, the guide pin was placed more distally and anteriorly than the anatomic center of the femur footprint, under arthroscopy.	NA	3D-CT: the placement of the femoral tunnel and tibial tunnel, the femoral tunnel angles. MRI: the signal intensity of the ACL graft	41.5 ± 5.9
Jarvis (2021)	Retrospective, nonrandomized	III	20	13.8	10:10	NA	NA	A flexible guide pin with a centering sleeve was advanced through the tibial tunnel and mated with the guide within the joint. The guide was hooked on the back wall of the lateral notch and the pin was centered over the native ACL footprint. With the knee at 90–95° of flexion, the flexible guide pin was advanced through the lateral femur and out the skin of the anterolateral thigh. A flexible reamer matching the graft diameter was advanced over the pin, and TT drilling of the femoral tunnel was performed to a depth of 25–30 mm.	NA	AP Radiograph: femoral tunnel angle, location of femoral tunnel on the AP view. Lateral Radiograph: location of femoral tunnel on the lateral view	24
da Silva (2017)	Retrospective cohort	III	17	37.1	15:2	The hamstring tendon	Autologous	With the arthroscope inserted into the medial portal, certain adjustments were made both in the degree of knee flexion and obliquity of the guide, and some attempts were frequently made until best positioning was achieved. With the knee flexion of around 65°, an ACL	NA	3D-CT: the location of the center of the femoral tunnel.	NA

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Table 2 (*continued*)

Lead author (Year)	Study design	Level of evidence	Sample size	Mean age (years)	Sex, male: female, n	Graft type	Source	Measured parameters			
								Surgical technicalities	Clinical outcomes	Radiographic results	Mean follow-up period (months)
								femoral offset guide was introduced into the tibial tunnel and rotated so that the femoral guide pin would attain the position as close as possible to the place demarcated on the femur.			
Chang (2011)	Retrospective, nonrandomized	III	55	31.8	39:16	The semitendinosus and gracilis tendon	Autologous	The angle of the tibial guide was set to 50° and the starting point of the tibial tunnel was placed midway between the posterior cortex of the proximal tibia and the medial margin of the tibial tuberosity. The intra-articular point of the tibial guide was placed at a position 1–2 mm medial and anterior to the center of the native tibial footprint of the ACL. If necessary, the femoral aiming guide was rotated laterally to achieve the target femoral position.	NA	Intraoperative direct measuring device: the length of the femoral tunnel. Radiographic Measurements: femoral tunnel position.	12
Silva (2010)	Prospective cohort	II	20	24	18:2	The semitendinosus and gracilis tendon	Autologous	The Howell 65° Tibial Guide was inserted through the medial portal to gauge the space between the PCL and the lateral femoral condyle, and a wallplasty was done until the space between the PCL and the lateral femoral condyle exceeded the diameter of the graft by 1 mm. A femoral aimer was inserted through the tibial tunnel, hooked over the posterior edge of the intercondylar notch and rotated laterally to place the tunnel even more obliquely.	NA	3D-CT: the location of the center of the femoral tunnel, tibial angle.	NA
Hussin (2018)	Prospective randomized	I	30	29	NA	The semitendinosus and gracilis tendons	Autologous	Tibial tunnel starting point is about 20 mm below the medial plateau and about 20 mm from the edge of the tibial tubercle.	Subjective evaluations: IKDC, Lysholm score; Objective evaluations: IKDC knee examination.	X-ray A-P views and lateral views: sagittal tibial graft angle, graft inclination angle, femoral tunnel	12

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Table 2 (*continued*)

Lead author (Year)	Study design	Level of evidence	Sample size	Mean age (years)	Sex, male: female, n	Graft type	Source	Measured parameters			
								Surgical technicalities	Clinical outcomes	Radiographic results	Mean follow-up period (months)
								The tibial drill guide is positioned at 40° to the long tibial axis in the coronal plane. The femoral guiding device should be 2 mm smaller than the size of tibial tunnel to allow more free mobility in the tunnel. External rotation of the femoral guide after hooking its shoulder over the top position will give extra few degrees of obliquity.		placement, tibial tunnel placement	
Han (2019)	Retrospective, nonrandomized	III	45	31	NA	The hamstring tendon	Autologous	The tibial drill guide is placed at an angle of 50° in the sagittal plane and 20° in the coronal plane. With the knee in 90° flexion, more anatomical femoral tunnel was created by applying anterior drawer force, varus stress, external rotation of the tibia and external rotation of the femoral offset guide and directing the jig towards the anatomic centre of the ACL footprint.	Subjective evaluations: IKDC, Lysholm score; Objective measurements: Lachman's, pivot shift, KT-1000 arthrometer measurements.	NA	36
Yu (2021)	Retrospective, nonrandomized	III	39	37	25:14	The semitendinosus and gracilis tendon	Autologous	The angle of the tibial guide was set to 50° and the starting point of the tibial tunnel was placed midway between the posterior cortex of the proximal tibia and the medial margin of the tibial tuberosity. The femoral offset aiming guide was passed through the tibial tunnel, and its hook was placed at around the 10:30 clock position (right knee)/ 1:30 clock position (left knee) of the over-the-top area of the lateral intercondylar notch. If necessary, the femoral aiming guide was rotated laterally to achieve the target femoral position.	NA	3D-CT: the position of the femoral tunnel and tibial tunnel	

anteromedial portal technique, outside-in technique), only the results of modified TT drilling techniques were included. Any inconsistencies between the investigators were resolved by joint review of the involved articles. Missing data were requested by contacting the authors via email.

2.5. Study quality assessment

The purpose of quality assessment was to determine aspects of methodological quality and study design common to all included studies. Two independent investigators assessed included studies for risk of bias according to a 12-item scale [27]. Methodological quality was categorized as follows: a score of 9–12 was considered high quality, 5 to 8 moderate quality, 0 to 4 low quality. Discrepancies between investigators were resolved via consensus discussion with a third investigator (W.S.B). For each item, studies were evaluated as fulfilling or not fulfilling the criterion.

2.6. Statistical analysis

All data were analyzed using StatsDirect V.2.8 (Altrincham, UK). Pooled continuous outcomes were analyzed using random-effects meta-analyses and standardized mean differences (SMD). Pooled dichotomous outcomes were combined via a proportion meta-analysis using a random effects model and odd ratios (OR). Studies included in the mate-analyses were weighted for individual study sample size. The pooled SMD were interpreted according to Cohen's guidelines [28]. Data of clinical outcomes and radiological results from each study in addition to the pooled results were summarized in forest plots. The SMD and 95 % confidence interval (CI) were calculated for clinical and radiological outcomes.

3. Results

3.1. Search strategy, study quality assessment and characteristics

The literature search initially yielded a total of 2064 articles. After the removal of duplicate articles, 1266 articles remained, of which 1201 were excluded based on a review of the title and abstract according to the predefined selection criteria. Sixty-five articles were obtained in full text and examined, and from these, 49 articles were excluded (Fig. 1).

Details of risk of bias assessment for each study were shown in Table 1. Overall, 3 studies that explicitly used randomization and allocation concealment were considered high quality studies [20,29,30], and the remaining 13 studies were considered moderate quality (Table 1).

A summary of the patients examined, the surgical technicalities, the clinical and radiological outcome measures employed and focus of each study were shown in Table 2. Overall, 628 patients were evaluated in the 16 reviewed studies at a mean follow-up of 21.4 months (range, 12–41.5 months).

3.2. Subjective outcomes and laxity

Overall, a total of 189 patients reported IKDC subjective knee function scores at final follow-up, and the pooled SMD was 86.07 (95 % CI 79.84 to 92.31) [20,21,30–32]. A total of 237 patients reported the Lysholm scores, and the pooled SMD was 90.39 (95 % CI 83.41 to 97.38) [20,21,30,32–34]. In total, 122 patients reported the Tegner scores, and the pooled SMD was 6.15 (95 % CI 3.96 to 8.33) [20,21,32]. A total of 194 patients reported anterior tibial translation, and the pooled SMD was 1.91 mm (95 % CI 0.76 mm–3.05 mm) [21,31,32,34] (Fig. 2).

3.3. Objective outcomes

Results of manual laxity tests, which included the pivot shift test, the Lachman test, and/or the anterior drawer test were reported in 6 studies [20,21,30,32–34]. In total, 92 % (95 % CI 80 %–99 %) of patients had a negative pivot shift test, 91 % (95 % CI 76 %–99 %) had a negative Lachman test, and 93 % (95 % CI 75 %–100 %) had a negative anterior drawer test. Pooled IKDC objective classification data from two studies (n = 82) showed that 94 % (95 % CI 87 %–99 %) had objective knee function classified as 'normal' (IKDC category A) or 'nearly normal' (IKDC category B) (Fig. 3) [20,30].

3.4. Radiological outcomes

Overall, eight studies (353 participants) reported the femoral tunnel position at final follow-up [20,22,29,32,34–37]. The pooled SMD for distance from the femoral tunnel center parallel to the Blumensaat's line was 30.08 % (95 % CI 28.25 %–31.91 %). The pooled SMD for distance from the femoral tunnel center perpendicular to the Blumensaat's line was 37.72 % (95 % CI 35.75 %–39.70 %). The pooled SMD for femoral tunnel angle in the coronal plane (353 participants) was 48.27° (95 % CI 43.14°–53.40°) [20,22,29,32,34–37]. A total of 255 participants (6 studies) reported the femoral tunnel length, and the pool SMD was 33.98 mm (95 % CI 29.03 mm–38.93 mm)(Fig. 4) [20,22,29,32,33,38].

The tibial tunnel position was evaluated in the 3D CT model (5 studies, 179 patients) [22,29,30,32,35]. The pooled SMD for distance in the anteroposterior aperture position of the tibial tunnels was 38.38 % (95 % CI 36.56 %–40.20 %), and the pooled SMD for

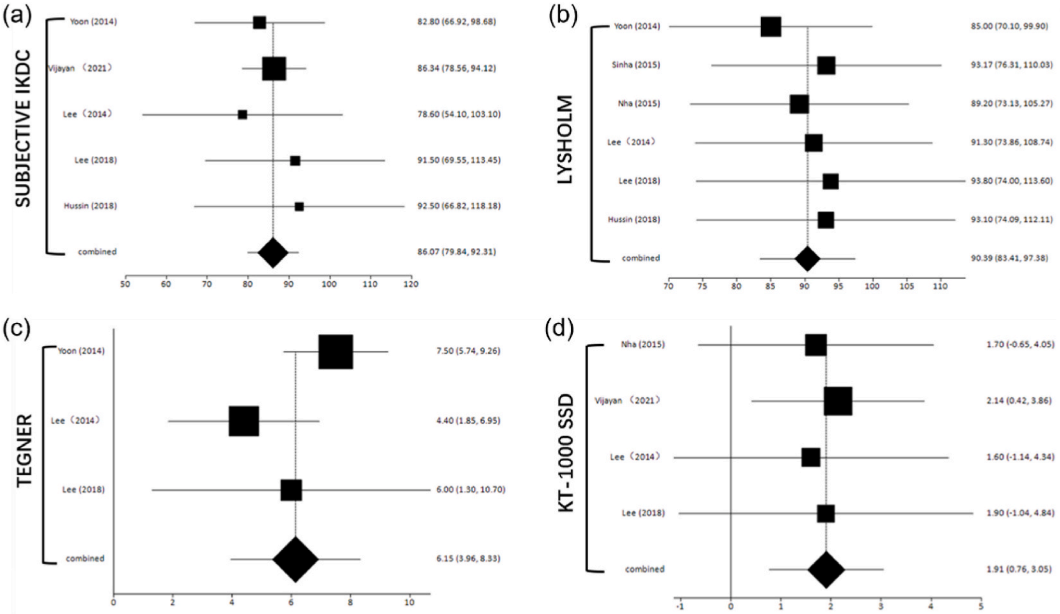

Fig. 2. Forest plots for the pooled standardized mean difference of (a) subjects International Knee Documentation Committee (IKDC) score, (b) Lysholm score, (c) Tegner score, and (d) KT-1000 arthrometer side-to-side difference (SSD) in anteroposterior laxity.

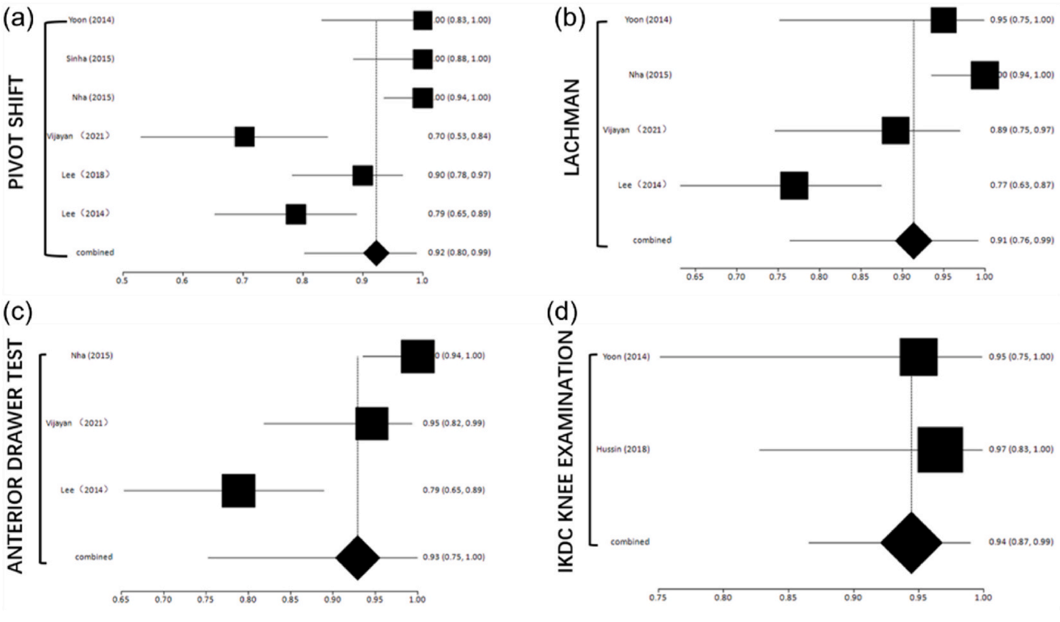

Fig. 3. Forest plots for the pooled rates of (a) negative pivot-shift test, (b) negative Lachman test, (c) negative anterior drawer test, and (d) IKDC knee examination score A or B.

distance in the mediolateral aperture position of the tibial tunnels was 47.95 % (95 % CI 45.60 %–50.30 %). A total of 60 participants reported the tibial tunnel length, and the pooled SMD was 37.82 mm (95 % CI 32.70 mm–42.93 mm) (Fig. 5) [22,29].

4. Discussion

The most important findings of the present review were that the anatomic position of the femoral tunnel can be achieved using the modified TT techniques, with these methods yielding satisfactory self-reported knee function and improved knee stability at a long-term follow-up. Anatomical placement of ACL graft is important for restoring normal knee function and stability after ACL reconstruction. Our findings provide surgeons with evidence to support the use of modified TT techniques as a viable option for ACL

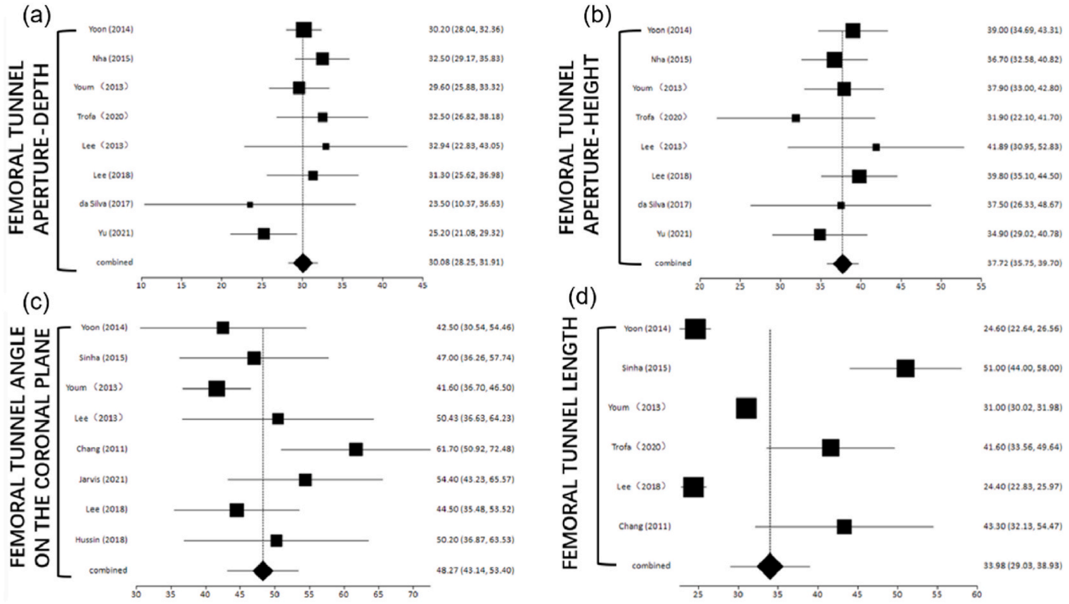

Fig. 4. Forest plots for the pooled standardized mean difference of (a) femoral tunnel aperture depth, (b) femoral tunnel aperture height, (c) femoral tunnel angle on the coronal plane, and (d) femoral tunnel length.

reconstruction.

The TT technique in ACL reconstruction is a common, relatively easy, and reproducible procedure [21]. Positioning of the femoral tunnel is constrained by the tibial tunnel, with femoral tunnel placed more anterior and superior in the femoral condyle [39]. Traditional TT technique has been reported to result in a vertically oriented ACL graft and rotational instability [12]. Recently, many attempts have been focused on producing an anatomic femoral tunnel, including modification of the angles and location of the tibial tunnel, and adjustment of intraoperative tibial position [20,21,30,33,34,40]. It has been demonstrated that an anatomic femoral tunnel could be achieved using a modified TT technique for anatomic ACL reconstruction [20]. Using a modified TT technique with a more proximal and medial tibial tunnel starting point, the center of the femoral tunnel was in the anatomic footprint in the height of the femoral condyle [35]. The tibial tunnel angle of 45–50° to the medial joint line in the coronal plane is appropriate for creating an anatomic femoral tunnel [20]. These details underscore the technical considerations necessary to achieve anatomical placement

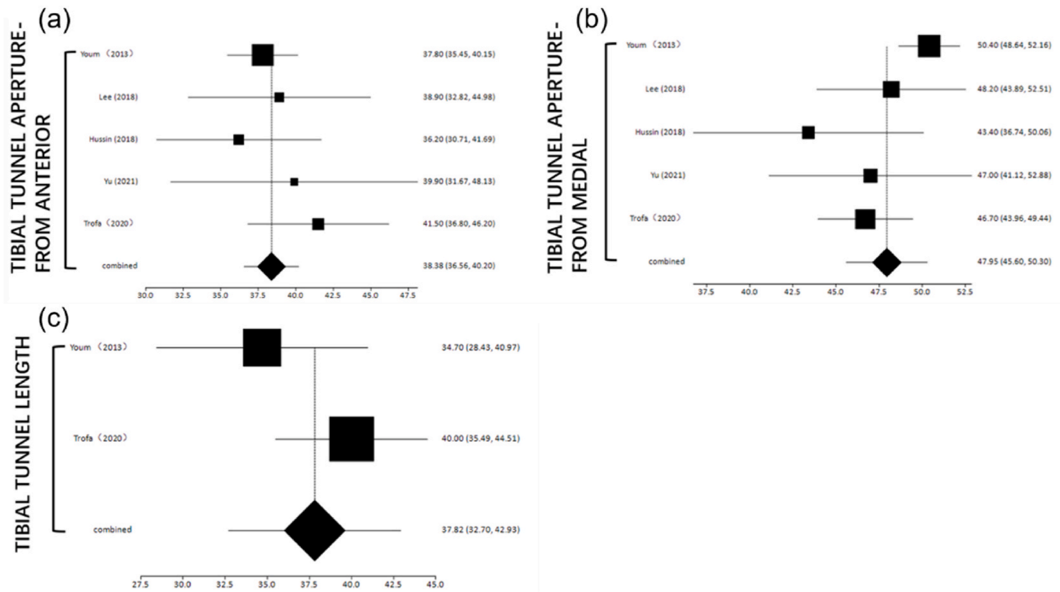

Fig. 5. Forest plots for the pooled standardized mean difference of (a) anteroposterior position of the tibial tunnels, (b) mediolateral position of the tibial tunnels, and (c) tibial tunnel length.

during ACL reconstruction procedures.

The quadrant method using 3D CT scan is commonly used for evaluating the tunnel position for ACL reconstruction [22,35]. In our study, the mean distance in the anteroposterior aperture position of the tibial tunnels was 38.4 %, and the mean distance in the mediolateral aperture position of the tibial tunnels was 48.0 %. Hussin et al. [30] reported that the mean anterior-to-posterior distance for the tunnel center location was 37.8 % and the mean medial-to-lateral distance was 50.4 % in the AM group. Our results were similar to the location of the tibial tunnel reported in the AM group. The mean position of the femoral tunnel (depth:30.1 %, height:37.7 %) was obtained in this review by means of 3D CT in a series of ACL reconstruction with modified TT techniques. The mean ACL femoral footprint in cadaveric knees that also used the quadrant method for calculation was 29.9 % in depth and 33.2 % in height [3]. It indicates that the average tunnel positions achieved using the modified transtibial technique were close to the anatomical footprint of the ACL. It has been reported that the femoral tunnel position was 28.0 % in depth and 37.2 % in height after ACL reconstruction with AM portal technique [41]. This statement indicates that while the modified TT technique may not achieve the exact anatomical position desired for the femoral tunnel, the average position observed in the study was comparable to what is typically reported with the AM portal technique. This comparison highlights the effectiveness and relative positioning achieved by the modified TT approach.

The obliquity of the femoral tunnel was defined as the angle between the reamed femoral tunnel and femoral condyle tangent line in the coronal plane [26]. The smaller femoral tunnel angle in the coronal plane was correlated with the more acute graft bending angle, which affected the incomplete maturity of the ACL graft [32]. The modified TT technique (48.3°) in our study resulted in a more oblique femoral tunnel compared with traditional TT technique (58.8°) [20]. Our coronal angle of the femoral tunnel was higher than the results (34.1°, 39.1°) from previous AM portal technique [22,35]. An in-vitro study showed that a femoral graft length of less than 25 mm and a tibial graft length of less than 30 mm may adversely affect graft healing [16]. The modified TT technique had a longer mean femoral tunnel length than the AM portal technique as previously reported (34.0 mm vs 30.2 mm) [20]. Additionally, the modified TT technique had a longer tibial tunnel length than the AM portal technique as previously reported (37.8 mm vs 34.0 mm) [29]. When selecting surgical techniques, it is crucial to consider both the obliquity of the tunnel and its length, as these factors can significantly impact graft healing [32]. In our study, the modified TT technique resulted in a less oblique femoral tunnel and a longer tunnel length compared to the AM technique, which may facilitate graft healing.

Although the ability of these modified TT techniques to achieve anatomic ACL reconstruction was reported, render satisfactory clinical outcomes has been unclear [20]. Good clinical outcomes including subjective evaluations and physical examinations were observed with the modified TT technique in the present study. Regarding the subjective outcomes, the average IKDC (86.1) and Lysholm (90.4) can be considered satisfactory, especially in view of the long follow-up. IKD scores ranging from 85 to 100 points indicate asymptomatic, stable knees with normal function during sports activities [42]. Lysholm scores ranging from 84 to 94 points suggest good knee function [42]. We also noted optimal results regarding activity level, with an average Tegner score of 6.2, which corresponds to recreational sports-badminton, tennis, handball, and jogging at least 5 times per week. Another interesting finding was the good stability, with only 10 % of patients presenting a negative Lachman or pivot shift test. In addition, a satisfactory outcome was found for anterior tibial translation, with an average KT-1000 arthrometer SSD of 1.9 mm at final follow-up. The overall good objective results reveal that the reconstructed ACL function is stable over time [43]. This indicates that the modified TT technique may facilitate knee stability, thereby contributing to the favorable clinical outcomes observed in this study.

Certain limitations need to be acknowledged, such as the inclusion of retrospective studies that lacked randomization and blinding. Some included studies had modest sample sizes, resulting in significant heterogeneity due to differences in study design, surgical techniques, and patient diversity. Another limitation is the lack of standardization in the modified TT technique across the included studies. Future studies should ensure more consistent reporting of vital information, including surgical plans, clinical and radiological outcomes. This review did not include a comparison with other techniques. However, the authors utilized the mean position of the femoral tunnel derived from previous studies for reference. Furthermore, the studies had relatively short follow-up periods, thereby failing to thoroughly investigate postoperative outcomes. To enhance the representativeness of the data, future studies should employ large prospective cohorts with long-term follow-up.

5. Conclusions

Our findings are clinically relevant, showing that a modified TT technique can create an anatomic femoral tunnel, with improved knee stability and satisfactory clinical outcomes. This investigation has also shown that the modified TT technique can maintain optimal tunnel length and angle. These findings provide surgeons with evidence to support the use of modified TT techniques as a viable option for ACL reconstruction. Future long-term follow-up studies should determine whether these modifications in TT ACL reconstruction could produce better clinical outcomes compared with other techniques.

Data availability statement

The data that support the findings of this study are available from the corresponding author upon reasonable request.

Ethical review committee statement

This study design and protocol were performed in accordance with the PRISMA Statement. The protocol was registered previously on PROSPERO CRD42022334103.

CRediT authorship contribution statement

Ling Zhang: Writing – original draft, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Junjie Xu:** Methodology, Formal analysis, Data curation, Conceptualization. **Ye Luo:** Software, Methodology, Investigation, Formal analysis. **Luqi Guo:** Software, Resources, Formal analysis. **Shaobai Wang:** Writing – review & editing, Visualization, Validation, Supervision, Conceptualization.

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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