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A Systematic Review of Noncircular (Rectangle, Oval) Femoral Tunnel Anterior Cruciate Ligament Reconstruction: Does it Improve Outcomes?

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A Systematic Review of Noncircular (Rectangle, Oval) Femoral Tunnel Anterior Cruciate Ligament Reconstruction: Does it Improve Outcomes?

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Abstract

Purpose: The purpose of this study is to systematically review the clinical and biomechanical studies regarding noncircular (rectangular and oval) femoral tunnel anterior cruciate ligament reconstruction (ACLR). We hypothesized that noncircular femoral tunnel ACLR has its advantages in unique situations while maintaining comparable clinical and radiographic outcomes when compared to conventional techniques. **Methods:** A systematic review of the literature was performed in PubMed and Scopus databases to identify published articles on the clinical outcomes of noncircular (rectangle and oval) ACLR. The results of the eligible studies were analyzed in terms of instrumented laxity measurements, Lachman test, pivot-shift test, Lysholm and Tegner scores, objective and subjective International Knee Documentation Committee (IKDC) scores, and surgical complications/failures. A meta-analysis was performed on Lysholm scores and KT side-to-side data comparing noncircular ACLR with the conventional round technique. **Results:** A total of 22 papers for the rectangle group (n = 1314) met the inclusion criteria. With an average follow-up of 15.8 months (±10.4 months), the mean reported Lysholm score was 97.8 (±0.80) and the mean reported KT-1000 arthrometer measurement was 1.2 (±1.9). When comparing the rectangle technique to the conventional round, no significant differences were seen regarding the Lysholm score ($P = 0.95$) or KT-1000 arthrometer measurements ($P = 0.14$) at the final follow-up. In the oval group, a total of 5 studies (n = 322) met the eligibility criteria. With an average follow-up of 20.2 months (±13.7 months), the mean reported Lysholm score was 94.4 (±2.0), the mean IKDC subjective was 90.4 (±1.2), and the mean KT-1000 arthrometer measurement was 1.6 (±0.4). The scarcity of randomized controlled trials available for this analysis limited the amount of data available for meta-analysis. **Conclusions:** Noncircular femoral tunnel ACLR has shown reasonable and comparable clinical outcomes to the conventional technique, demonstrating no difference between the two techniques and making it a valuable option for primary or revision ACLR.

Keywords: Anterior cruciate ligament reconstruction, anterior cruciate ligament tear, knee, knee arthroscopy

Introduction

The shape of the anterior cruciate ligament (ACL) femoral attachment is broad and flat and consists of two bundles. The anteromedial (AM) bundle is tight in flexion from 45° to 60° and the posterolateral (PL) bundle is tight in extension.[1] Several studies have shown that the conventional single bundle (SB) ACL reconstruction (ACLR) is successful in the restoration of the anterior tibial translation but does not effectively restore rotational stability.[2-4] The rate of return to sports is not favorable after conventional ACLR with studies reporting only 45%–65% of patients returning to preinjury level activity.[5,6]

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Anatomic studies have shown that the shape of the femoral attachment of the ACL is not round, but rather oblong, and a more anatomic reconstruction can be achieved by creating an oval or rectangular shape of the attachment.[7] Shino *et al*. described

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the rectangular ACLR technique, claiming that the rectangular attachment more closely resembles the shape of the native ACL femoral attachment.[8] Noh *et al*. demonstrated another noncircular femoral tunnel ACLR with an oval footprint.[9]

The purpose of this study is to evaluate the clinical and biomechanical studies regarding noncircular (rectangular and oval) femoral tunnel ACLR. In addition to investigating the utility of noncircular femoral tunnel ACR, a meta-analysis was performed to compare the clinical outcomes and survival of these techniques. We hypothesized that noncircular femoral tunnel ACLR has its advantages in unique situations while maintaining comparable clinical and radiographic outcomes when compared to conventional techniques.

Methods

A comprehensive search of PubMed and Scopus databases was performed with the use of the following keywords: "rectangle," "oval," "oblong," "anterior cruciate ligament," and "ACLR." All articles in the English language up to February 1, 2022, were included, including articles published online. The titles and abstracts of the potentially relevant studies were reviewed and articles that included human subjects and were deemed potentially relevant were retrieved for more detailed evaluation.

The study included all papers addressing the clinical outcomes of nonround femoral tunnel ACLRs. The search was limited to the English language and human studies. Articles that were excluded discussed studies that failed to meet the inclusion criteria, specifically those that did not report clinical outcomes on human subjects, review articles, that did not involve the use of noncircular femoral and/or tibial tunnels in ACLR. After removing the duplicates, the full text of the papers was evaluated with the application of predetermined inclusion and exclusion criteria. The references of the included papers were screened to find any paper that was not found in the primary search. Of the papers included in our study, 22 discussed rectangular tunnel reconstruction and 5 discussed oval tunnel reconstruction [Figures 1, 2 and Tables 1, 2].

The number of patients, average follow-up and clinical outcome data were extracted from each paper, and in papers

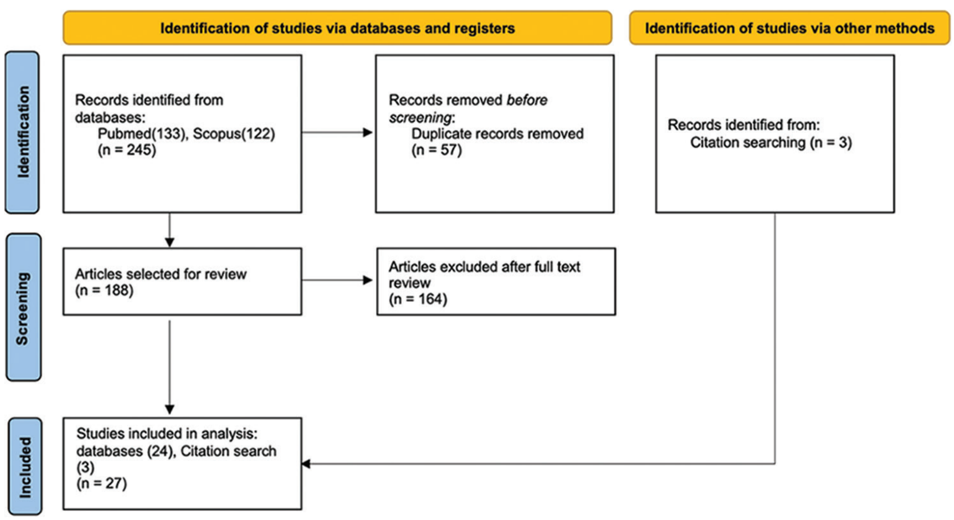

Figure 1: PRISMA Flowchart showing the identification, selection, eligibility, and inclusion of primary studies. PRISMA: Preferred reporting items for systematic reviews and meta-analysis

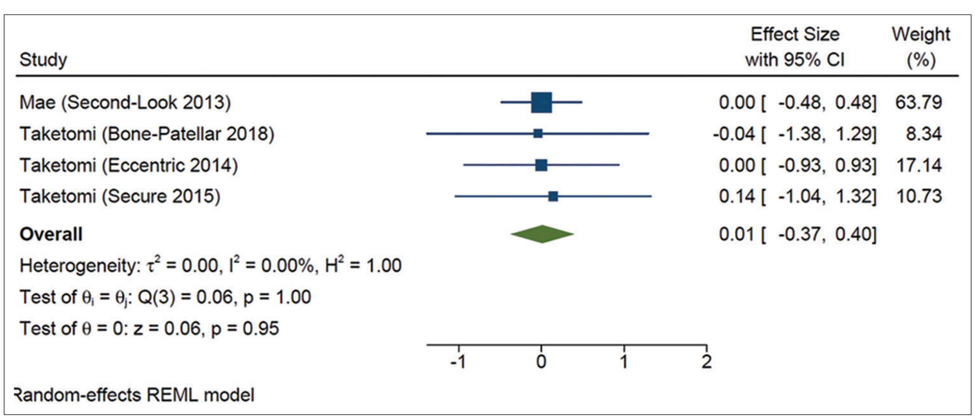

Figure 2: Forest plot showing standard mean differences in Lysholm score between rectangular and round femoral tunnel ACLR. No significant difference was found between the two techniques. ACLR: Anterior cruciate ligament reconstruction, CI: Confidence interval, REML: Restricted Maximum Likelihood

Table 1: Study characteristics

Author	Year	Journal	Country	Design	Period	LOE	Sample Size (*n*)	Surgery	Age (years)	Follow-up (months)
Lui *et al*.	2018	Am J Transl Res	China	PCS	2015-2016	II	40	Oval (*n*=40)	29.7 (18-40)	0.5
Noh *et al*.	2011	JARS	Korea	PCS	2006-2008	II	74	Oval (*n*=34)	24.5 (19-47)	32.4
Zhang *et al*.	2019	Am J Transl Res	China	PCS	2015-2016	II	80	Oval (*n*=40)	29.2 (+/- 8.0)	24
Wen *et al*.	2019	KSSTA	China	PCS	2016-2017	III	108	Oval (*n*=39)	31.4 (+/- 9.9)	24
Petersen *et al*.	2013	AOTS	Germany	RCS	2011	IV	24	Oval (*n*=44)	N/A	N/A
Mae *et al*.	2019	JOS	Japan	PCS	2007-2011	II	467	Rectangle (*n*=233)	22.5 (13-39)	24
Sasaki *et al*.	2016	AJSM	Japan	RCT	2007-2009	I	150	Rectangle (*n*=69)	27.0 (+/- 11.9)	38.9
Inoue *et al*.	2015	Kurume Med J	Japan	RCS	N/A	IV	40	Rectangle (*n*=40)	22 (13-45)	N/A
Amano *et al*.	2019	KSSTA	Japan	RCS	2012-2013	IV	32	Rectangle (*n*=32)	25.1	6
Takata *et al*.	2016	AOTS	Japan	RCS	2010-2014	IV	81	Rectangle (*n*=42)	23.2 (+/- 8.4)	3
Hayashi *et al*.	2019	PLOS	Japan	PCS	2015-2017	III	42	Rectangle (*n*=42)	29.9 (+/- 10.1)	1
Take *et al*.	2015	AP-SMART	Japan	RCS	1996-2009	IV	133	Rectangle (*n*=111)	21.5 (13-44)	N/A
Taketomi *et al*. (Eccentric)	2014	JARS	Japan	RCS	2009-2012	IV	52	Rectangle (*n*=26)	27 (16-50)	12
Taketomi *et al*. (Secure)	2015	Joints	Japan	RCS	2009-2012	IV	34	Rectangle (*n*=34)	25 (16-50)	12
Taketomi *et al*. (Bone)	2018	J Knee Surg	Japan	RCS	2012-2014	IV	48	Rectangle (*n*=25)	32 (15-55)	25
Uchida *et al*. (Excellent)	2019	J ISAKOS	Japan	RCS	2012-2013	IV	20	Rectangle (*n*=20)	25 (+/- 10)	2
Uchida *et al*. (Relationship)	2018	KSSTA	Japan	RCS	2013-2015	IV	30	Rectangle (*n*=30)	20.4 (14-36)	6
Ohori *et al*.	2019	JOS	Japan	RCS	2010-2017	IV	18	Rectangle (*n*=18)	26.6 (16-38)	12
Nakase *et al*. (Clinical)	2021	BMC MSKD	Japan	RCS	2011-2016	IV	116	Rectangle (*n*=40)	24.8 (+/- 11.1)	24
Nakase *et al*. (Technique)	2016	Knee	Japan	RCS	2013-2015	IV	50	Rectangle (*n*=50)	N/A	0.25
Okimura *et al*.	2019	JOS	Japan	RCS	2005-2013	IV	50	Rectangle (*n*=50)	N/A	24
Tachibana *et al*.	2018	KSSTA	Japan	RCS	2009-2014	IV	61	Rectangle (*n*=61)	22.7 (14-48)	24
Kusano *et al*.	2018	JARS	Japan	PCS	2013-2014	IV	50	Rectangle (*n*=50)	24 (14-45)	24
Hiramatsu *et al*.	2018	KSSTA	Japan	RCS	2011-2014	III	149	Rectangle (*n*=149)	22.6 (14-46)	1
Shino *et al*.	2012	CORR	Japan	RCS	2004-2008	IV	18	Rectangle (*n*=18)	23 (15-34)	38
Suzuki *et al*.	2011	KSSTA	Japan	PCS	N/A	IV	20	Rectangle (*n*=20)	21 (16-36)	2
Masuda *et al*.	2018	KSSTA	Japan	PCS	2013-2014	IV	40	Rectangle (*n*=40)	20.5 (16-49)	5

that compared results of nonround femoral tunnels with conventional round tunnels, data from both groups was collected. Based on the comparative clinical outcome data, a meta-analysis was performed.

Data extraction and synthesis

The information extracted from the original studies included

Demographic data, follow-up data, and subjective and objective clinical scores. The mean values for subjective International Knee Documentation Committee (IKDC), Lysholm, and Tegner were extracted. The objective clinical evaluation was performed by extracting the objective IKDC, Lachman test, pivot shift test, and range of motion (ROM). In addition, the mean KT side-to-side difference and standard deviation (SD) measured in millimeters (mm) on anterior translation were extracted. Finally, the complications and failures that occurred during the follow-up period were noted. Data were extracted and tabulated into an Excel database by one author.

Analysis and methodological assessment

Articles were assessed for level of evidence and methodology using a modification of the original Coleman Methodology Score (CMS). Twenty-seven articles met the inclusion criteria and were therefore included in the meta-analysis and analyzed [Table 1]. Of the reviewed studies, there was one randomized controlled trial, nine prospective cohort studies, and 17 retrospective evaluations. The mean modified CMS was 53.9 ranging from 29 to 76 [Table 2]. The items that most affected the overall quality of the studies were: mean follow-up and type of study.

Statistical analysis

A random-effects meta-analysis model was used for these analyses; this assumes the observed estimates of treatment

Table 2: Modification of the original Coleman methodology score

Study	Part A							Part B			Total
	Study size	Mean follow-up	Surgical approach	Type of study	Description of diagnosis	Descriptions of surgical technique	Description of postop rehab protocol	Outcome Criteria	Producedure of assessing outcomes	Description of subject selection process	
Lui *et al*.	7	0	7	10	5	10	0	7	9	5	60
Noh *et al*.	7	4	7	10	5	10	5	7	9	5	69
Zhang *et al*.	7	4	7	10	5	10	5	7	9	5	69
Wen *et al*.	10	4	7	10	5	10	5	7	9	5	72
Petersen *et al*.	0	0	10	0	0	10	5	5	0	5	35
Mae *et al*.	10	4	7	10	5	10	5	7	5	5	68
Sasaki *et al*.	10	7	7	15	5	10	5	7	5	5	76
Inoue *et al*.	4	0	10	0	0	10	0	5	0	0	29
Amano *et al*.	4	0	10	0	0	10	5	7	4	5	45
Takata *et al*.	4	0	7	0	0	10	5	7	4	5	42
Hayashi *et al*.	4	0	10	10	0	10	0	7	0	5	46
Take *et al*.	10	0	7	0	5	10	0	5	4	5	46
Taketomi *et al*. (Eccentric)	7	4	7	0	5	10	5	7	4	5	54
Taketomi *et al*. (Secure)	4	4	10	0	5	10	5	7	9	5	59
Taketomi *et al*. (Bone)	4	4	7	0	0	10	5	7	4	5	46
Uchida *et al*. (Excellent)	0	0	10	0	5	10	5	7	4	5	46
Uchida *et al*. (Relationship)	4	0	10	0	5	10	5	7	4	5	50
Ohori *et al*.	0	4	10	0	5	10	5	7	4	5	50
Nakase *et al*. (Clinical)	7	4	7	0	5	10	5	7	4	5	54
Nakase *et al*. (Technique)	4	0	10	0	5	10	0	7	5	5	46
Okimura *et al*.	4	4	10	0	5	10	5	7	4	5	54
Tachibana *et al*.	7	4	10	0	5	10	5	7	4	5	57
Kusano *et al*.	4	4	10	10	5	10	5	7	9	5	69
Hiramatsu *et al*.	10	0	7	0	5	10	0	7	4	5	48
Shino *et al*.	0	7	10	0	5	10	5	7	0	5	49
Suzuki *et al*.	0	0	10	10	5	10	5	7	9	5	61
Masuda *et al*.	4	0	10	10	5	10	0	7	5	5	56
Total	5.0	2.3	8.7	3.9	3.9	10.0	3.7	6.8	4.9	4.8	53.9

effect can vary across studies because of real differences in the treatment effect in each study as well as sampling variability. Thus, even if all studies had an infinitely large sample size, the observed study effects would still vary because of the real differences in treatment effects.

A random‑effects meta‑analysis was performed on four subgroups of outcome measurement: Oval Subjective, Oval Objective, Rectangle Subjective, and Rectangle Objective. For each individual outcome measure, Hedge's G was used to estimate effect size, the calculation for the estimate and its standard error are below:

For each group (and each outcome available), calculate the mean difference (post – pre) and the SD of the difference:

$$s_{diff} = \sqrt{s_{pre}^2 + s_{post}^2 - 2 \times r \times s_{pre} s_{post}}$$

Using the mean difference, SD of difference, and sample size for each group (1 and 2) calculate the bias-adjusted version of Hedges G as

$$G = \left(1 - \frac{3}{4(n_1 + n_2) - 9}\right) * D \ wherre \ D = \left(\frac{\bar{d}_1 - \bar{d}_2}{s*}\right) \text{and}$$

$$s^* = \sqrt{\frac{(n_1 - 1)\, s^2_{diff1} + n_2 - 1)\, s^2_{diff2}}{n_1 + n_2 - 2}}$$

$$The\ SE\ for\ G\ is\ SE(G) = \left(1 - \frac{3}{4(n_1 + n_2) - 9}\right) * \sqrt{\left(\frac{n_1 + n_2}{n_1 n_2} + \frac{D^2}{2(n_1 + n_2)}\right)}$$

The overall effect size of each subgroup was generated and tested against a null hypothesis of Effect Size = 0, the *z*-score, 95% confidence interval, and *P* value are reported in the table. Each subgroup was tested for Heterogeneity, the I^2 value and its *P* value were also reported.

Results

A total of 22 studies for the rectangle group (*n* = 1314) met the inclusion criteria [Figure 1]. With a mean age of 24 (±3.4) and an average follow-up of 15.8 months (±10.4 months), the mean reported Lysholm score was 97.8 (±0.80) and the mean reported KT-1000 arthrometer measurement was 1.2 (±1.9) [Tables 3 and 4]. When comparing the rectangle technique to the conventional round technique, no significant differences were seen regarding the Lysholm score or KT-1000 arthrometer measurements at the final follow-up [Figures 2, 3 and Table 5]. In the oval group, a total of 5 studies (*n* = 322) met the eligibility criteria. With a mean age of 28.5 (±2.9) years and an average follow-up of 20.2 months (±13.7 months), mean reported Lysholm score was 94.4 (±2.0), the mean IKDC subjective was 90.4 (±1.2), and the mean KT-1000 arthrometer measurement was 1.6 (±0.4). When comparing the oval technique to the conventional round technique, no significant differences were seen regarding Lysholm score final follow-up [Figure 4 and Table 5].

Discussion

Through a systematic review and meta-analysis on noncircular femoral tunnel ACLR, this study was able to demonstrate that this technique has reasonable and comparable clinical outcomes compared to the conventional round technique as well as some biomechanical advantages as the noncircular graft more closely resembles the native ACL footprint.

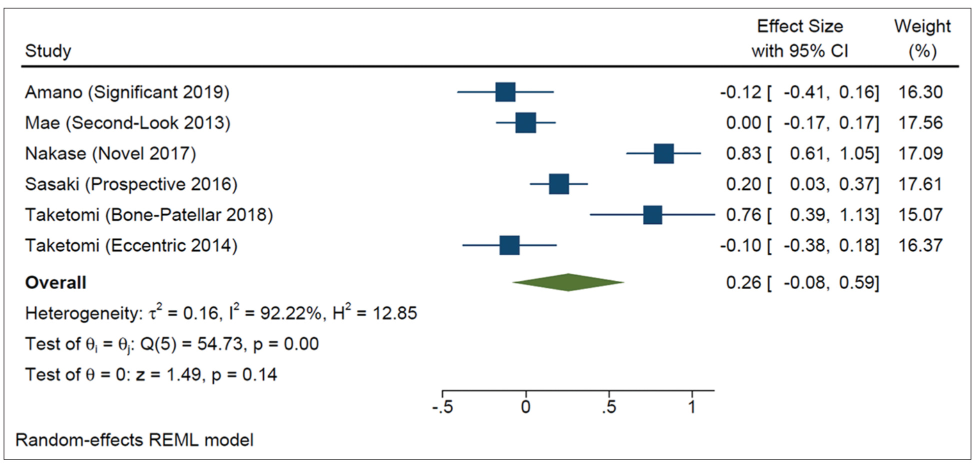

Figure 3: Forest plot showing standard mean differences in KT-1000 arthrometer measurements between rectangular and round femoral tunnel ACLR. When comparing the two techniques, no significant difference was found. ACLR: Anterior cruciate ligament reconstruction, CI: Confidence interval, REML: Restricted Maximum Likelihood

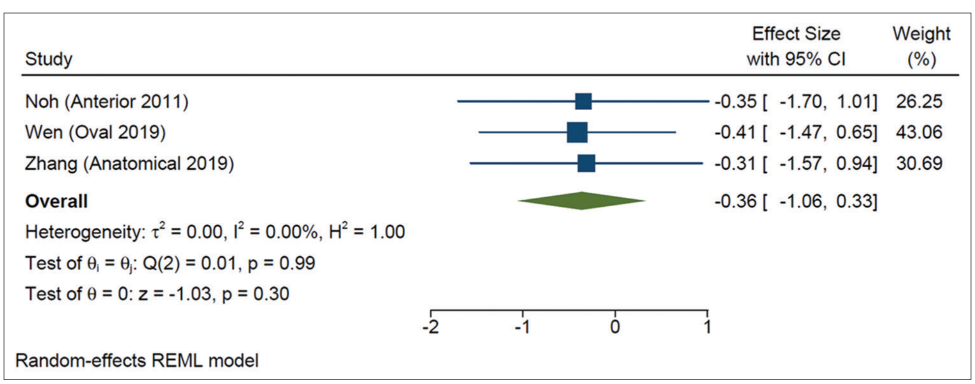

Figure 4: Forest plot showing standard mean differences in Lysholm score between oval and round femoral tunnel ACLR. When comparing both techniques, no significant differences were found. ACLR: Anterior cruciate ligament reconstruction, CI: Confidence interval, REML: Restricted Maximum Likelihood

Multiple studies have described techniques to accomplish anatomic rectangular tunnels and their advantages which have resulted in both minimal complications as well as clinical success. Shino *et al*. described a technique for the creation of rectangular tunnels.[8,10,11] The authors created a 10 mm wide graft made of two continuous 5-mm round tunnels along the long axis in the center of the attachment area that were then dilated using a 5 mm × 10 mm dilator and a rectangular 10 mm graft was then inserted. This rectangular bone-patellar tendon-bone graft was found to better mimic the fiber arrangement inside the native ACL.[12] Hayashi *et al*. described a similar technique but noted that the direction of the dilator should be adjusted under fluoroscopy before insertion, ensuring it is parallel to the line connecting the centers of the AM bundle and the PL bundle and posterior to the resident ridge.[13]

Fink *et al*. proposed a technique utilizing a quadriceps tendon (QT) graft along with rectangular bone tunnels.[14] Their study suggested that rectangular bone tunnels more closely recreate the native ACL attachments along with the QT graft which broad flat structure mimics the “ribbon-like” morphology of the native ACL. Their technique was described as simulating the native ACL rotation during knee ROM and thus improving biomechanics. These authors created the rectangular tunnels through the use of a rectangular rasp matched with the diameter of the graph. Once the tunnel was created and rasped to a depth of 25–30 mm, a dilator matching the graft size was inserted, and rough edges were removed with an arthroscopic shaver.

Noh *et al*. proposed an oval-footprint technique for ACLR, creating elongated femoral and tibial tunnels that are more representative of the native ACL footprint, which has been described as more oval-shaped rather than round.[9,15] To prepare an oval-footprint femoral tunnel, the authors reamed their initial femoral tunnel, which corresponded to the AM bundle, to 30 mm. The PL part of the tunnel, corresponding to the PL bundle, was reamed with the guide pin held steady on the wall. Their modified technique described the creation of the femoral tunnel transtibial, which is thought to result in a more elongated tunnel as the guide pin and reamer are more oblique to the intercondylar surface. Furthermore, an oval-shaped dilatator has been described by a number of authors to create oval-shaped bone tunnels more closely resembling the oblong femoral tunnel attachment.[16]

Table 3: Summary of patient demographic data

	Age (years)	Follow-up (months)
Oval	28.5 (+/- 2.9)	20.2 (+/- 13.7)
Rectangle	24.0 (+/- 3.4)	15.8 (+/- 10.4)

Table 4: Summary of mean clinical outcomes

	Subjective IKDC	Lysholm	KT-1000 SSD (mm)
Mean Oval	90.4 (+/- 1.2)	94.4 (+/- 2.0)	1.6 (+/- 0.4)
Mean Rectangle	N/A	97.8 (+/- 0.8)	1.2 (+/- 1.9)

Herbort *et al*. demonstrated a reconstruction technique in cadavers using a rectangular tunnel with a SB-bone-patellar tendon-bone (BTB) graft that resulted in significantly lower anterior tibial translation compared to the conventional round tunnel technique at 0° and 15° of flexion.[17] Their findings suggest that clinically, rectangular tunnel BTB ACLR may result in better anterior knee stability at low flexion angles. Biomechanically, Mae *et al*. demonstrated that the use of an anatomic rectangular tunnel technique in BTB-ACLR resulted in a force-sharing pattern similar to that of the normal ACL in response to anterior tibial load and during passive knee extension.[18] In addition, Nakase *et al*. noted that creating large oblong femoral tunnel attachments for oval grafts improves rotational and anteroposterior stability.[19]

There are numerous causes for ACLR failure, with femoral tunnel malpositioning being the most common one. The cross-sectional area of tunnels used in the rectangular graft technique was found to be 50 mm^2 as compared to the conventional round tunnel technique (79 mm^2), when a 10-mm wide BTB graft was used.[10] One-stage rectangular bone-patellar tendon-bone (BTB) grafts have been recommended for revision in cases of gross malpositioning of the femoral tunnel due to the previously mentioned cross-sectional area differences of rectangular grafts when compared to conventional round grafts. The smaller area allows for the creation of a new properly positioned tunnel that avoids overlap by allowing for greater space between previous tunnels and new tunnels while also preserving bone. When significant tunnel widening was present, bone grafting is recommended in conjunction with the rectangular graft.[10-12]

The revision of a failed double-bundle (DB) ACLR is further complicated by enhanced bone loss created by two femoral tunnels. Oftentimes, two stages ACLR and bone grafting are required.[20]

Table 5: Significant results after meta-analysis demonstrating no significant differences in Lysholm score or KT side-to-side measurements in noncircular anterior cruciate ligament reconstruction techniques

Significant Results After Meta-Analysis				
Variable	**Pooled OR/SMD**	**95% Confidence Interval**	**Sig/n.s.**	***I^2***
Oval Lysholm	-0.36	[-1.06 to 0.33]	n.s.	0.00%
Rectange Lysholm	0.01	[-0.37 to 0.40]	n.s.	0.00%
Rectangle KT side-to-side	0.26	[-0.08 to 0.59]	n.s.	92.22%

In the revision of the properly placed DB femoral tunnels, dilating the two tunnels with a rectangular dilator was advised.[10,12]

Several studies evaluated the outcome of the ACL anatomic rectangular reconstruction (ART) utilizing radiographic analysis.[21,22] The BTB graft healing improved with this technique because of the close contact and fit of the graft in the tunnel. There are two types of union in graft healing. In indirect union, the granulation tissue fills the gap and after callus formation the bone heals, union occurs. There is no observed granulation tissue and callus formation in a direct union. Suzuki *et al*. showed the BTB graft healed 8 weeks after surgery in the femoral tunnel and the snug fit of the graft in the tunnel resulted in direct union as the primary mechanism for healing.[22] Inoue *et al*. found that this procedure improved graft-tunnel healing around the femoral bone tunnel aperture for the PL bundle, a known weak point of DB ACLR.[23] Masuda *et al*. demonstrated that the healing and integration of BTB graft occurs earlier in the tibial tunnel compared to femoral tunnel.[21]

Femoral tunnel malposition has been shown to be the most common cause of graft failure, making graft placement a key aspect of the procedure, regardless of type of graft, and fixation technique.[1]

In the past, the effort was directed at positioning the center of the femoral tunnel at the isometric point, identified as the anterior-superior border of the ACL footprint, to achieve more native ACL function. Drilling the isometric point has resulted in several problems such as impingement at the posterior cruciate ligament or the intercondylar notch/wall and potentially poor rotational stability due to a more vertical graft orientation. As a result, more anatomically oriented approaches have since been investigated. Take *et al*. have demonstrated that rectangular grafts not only show a mean elongation most similar to that of the native ACL but also significantly superior biomechanical characteristics compared to the isometric round tunnel (IRT) procedure.[24,25] In a study by Forsythe *et al*. utilizing Dynamic three-dimensional, it was shown that the most isometric point is located at the center of the direct fiber insertion of the ACL and the junction of the intercondylar ridge and bifurcate ridge.[26]

While investigating the biomechanical differences between IRT and ART techniques, based on overall graft length changes, Take *et al*. found a significant difference in length change between the IRT and ART groups, 1.0 ± 0.7 mm versus 3.4 ± 0.9 mm, respectively ($P < 0.001$).[24] These findings suggest the ART technique more closely replicates the biomechanical function of the native ACL, which has an intrinsic length change of 3–6 mm.

Sasaki *et al*. demonstrated that the ACL-ART technique provides more coverage of the ACL attachment compared to the conventional round tunnel.[7] In addition, Hayashi *et al*. showed with this technique, 92.9% of the femoral tunnels were located behind the resident ridge and 7.1% had some overlap on the resident ridge. They concluded that the high rate of anatomic femoral tunnel placement occurred because the rectangular shape of the tunnel allowed for better fitting and placement of the ACL footprint.[13]

Femoral tunnel widening can be considered a complication of ACLR as this enlargement may interfere with the creation of a new bone tunnel when anatomical revision reconstruction is performed. The cause of this enlargement can be attributed to a number of mechanical and biological factors.[27,28] In addition, greater tunnel widening has been reported in ACLR using hamstring grafts than with the use of BTB grafts.[29-31] Tunnel enlargement is a significant consideration in ACLR not only due to the difficulties faced when creating a new tunnel for revision ACLR and the need for bone grafting but also its effect on graft healing and maturation within the tunnel.[32-34]

A number of studies have investigated how femoral tunnel widening is affected by the use of a noncircular ACLR technique as compared to a standard round one.[27,35-37] The rounded rectangular bone tunnel and the oval tunnel both showed better compression of cancellous bone that led to increased bone density and osteosclerosis. Both techniques also helped in minimizing heat-related bone damage. Matching the bone graft to the bone tunnel wall and a well-fitted graft to the wall in the rectangular technique prevents micromotion and invasion of the synovial fluid into the tunnel.[27]

Uchida *et al*. found a correlation between femoral tunnel enlargement and the position of the distal portion of the femoral bone plug, suggesting the position of the deep plug in the tunnel is a risk factor for femoral tunnel enlargement.[38] They also suggested minimizing this risk by deviating the harvest site in the patellar tendon to match the shape of the tunnel aperture. Taketomi *et al*. demonstrated that the use of an anatomical rectangular ACLR using Bone-patellar tendon-bone (BPTB) graft resulted in a lower incidence of bone plug migration and a shorter mean distance of bone plug migration when compared to DB-ACLR with a hamstring tendon (HT) graft.[39] They theorized that this decrease in incidence of bone plug migration could be due to the higher friction between the bone plug and the bone socket making it less movable than compared to the soft tissue and the bone socket.

Meta-analysis

The concept of rectangular tunnels in the setting of both primary and revision ACLR has a number of biomechanical advantages as the noncircular graft more closely resembles the native ACL footprint compared to the conventional technique. The meta-analysis of the clinical outcomes of the ART showed that there were no differences between ART utilizing BTB grafts and the conventional round femoral tunnel technique.

When comparing rectangular tunnel ACLR with conventional round tunnel, a number of studies reported no significant difference in clinical outcomes between the two groups.[15,32,33,40] Nakase *et al*. compared the area of the femoral tunnel and clinical results between conventional single bundle

ACLR (ASBR) and rounded rectangular femoral tunnel ACL reconstruction (RFTR).[41] These authors found that compared to ASBR group, RFTR showed better anteroposterior stability (0.8 ± 1.1 mm vs. 1.8 ± 1.2 mm; $P < 0.01$), improved rotational laxity (negative pivot shift, 93.3% vs. 82.5%; $P < 0.01$), created a larger femoral tunnel area (52.7 ± 4.8 mm^2 vs. 47.0 ± 7.3 mm^2; $P < 0.01$), had better Lysholm scores (98.9 ± 2.4 vs. 97.6 ± 3.3; $P < 0.01$).

Inui *et al*. compared the clinical outcomes DB-ACLR using a HT autograft and rectangular femoral tunnel ACLR with BTB autografts. These authors found the rectangular tunnel BTB group showed improved anterior knee stability compared to the DB-HT group. Furthermore, this study found significant differences in other objective or subjective evaluations between the two techniques.[42]

Hayashi *et al*. demonstrated that the use of the rectangular femoral tunnel resulted in an average return to sport time of 10.4 ± 2.5 months and 78.8% return to the same competitive level before injury.[13] In addition, 66.7% of cases returned to sports without recurrence, which is comparable to reported 65% return rate in conventional ACLR.[6]

Several studies demonstrated the clinical efficacy of an oval femoral tunnel technique compared to that of the conventional round technique. Noh *et al*. found improved the clinical outcome scores, specifically Lysholm, with modified oval tunnel ACLR as compared to the conventional technique (median score of 94, range 75–98) versus a median score of 96 (range 76–98) in the oval-footprint group at the last follow-up ($P < 0.048$). Other clinical outcome variables investigated were not found to be significantly different between the two groups.[9]

Wen *et al*. compared the efficacy between ACLR using the oval femoral tunnel technique[9] and the conventional round tunnel technique using hamstring autograft.[35] These authors found that the oval femoral tunnel technique resulted in higher Lysholm scores (97.1 ± 3.9 vs. 94.8 ± 5.6, $P = 0.031$), higher IKDC subjective scores (92.0 ± 2.6 vs. 89.0 ± 3, $P < 0.001$), improved postoperative pivot shift test (1/37 vs. 10/65, $P = 0.048$), and improved graft maturity as demonstrated by a lower mean signal/noise quotient in the postoperative magnetic resonance imaging (MRI) (2.7 ± 0.9 vs. 3.6 ± 1.1, $P < 0.001$) at 2-year follow-up. This study found no statistically significant differences in Visual analog scale (VAS) score, Lachman's, knee ROM, and graft status or synovium coverage determined by second-look arthroscopic evaluation between the two groups at the final follow-up. The authors concluded that the patients in the oval femoral tunnel group had better knee stability and function, which was consistent with the findings of Noh *et al*.[9]

Zhang *et al*. have supported similar findings demonstrating improved Tegner scores, rotational stability via pivot-shift tests, and earlier graft maturation as seen on MRI in the oval group when compared to conventional techniques at 2-year follow-up.[16]

A significant finding in a number of studies investigating the rectangular tunnel technique when performing primary ACLR was that no significant increase in intraoperative or postoperative complications was observed.[21-23,27,32,39] Sasaki *et al*. demonstrated that the re-injury injury rate was 7.8% in the DB-ACLR hamstring graft DB-HT group and 4.1% in the rectangular SB patella tendon graft rectangular-tunnel SB (RTSB)-PT group.[40] Notably, they reported no graft failure without a traumatic episode. In Hayashi *et al*.'s study, a partial fracture of the BTB bone fragment was observed in two patients in ACL-ART patients, but no serious complications including neurovascular injury were observed.[13] Furthermore, they stated that 4 incidences of recurrence (3 within 1 year of surgery) had also occurred; however, all were due to poor compliance. Taketomi *et al*. demonstrated loss of flexion of >5° compared with the contralateral knee in one patient (4%) from each group in a study comparing the DB-HT and RTSB-PT groups.[33] Uchida *et al*. observed three cases of bone plug extrusion from the extra-articular tibial tunnel aperture. For these cases, the bone plugs were shortened or partially removed.[38] A partial posterior tunnel wall blowout was observed in the Nakase *et al*.'s study, however, the damage was noted to be minimal and was corrected using normal techniques.[19] In their investigation, using the rectangular tunnel technique in revision ACLR, Shino *et al*. demonstrated one of the 18 patients re-ruptured the graft at 28 months postoperatively.[12]

Of the studies investigating the oval femoral tunnel technique, three experienced no intraoperative or postoperative complications in either group.[16,36,43] In the study performed by Noh *et al*., one patient in the oval technique group lost 5° of extension, and all others regained normal full extension. An additional one subject in the oval technique group sustained an injury playing basketball requiring revision surgery.[9]

In a comparison between the oval femoral tunnel and rectangular femoral tunnel techniques, Nakase *et al*. demonstrated that the rectangular technique provides a more flat graft-bone junction than the oval one. Hence, there is more room to increase the size of the femoral tunnel without roof impingement in rectangular technique particularly in patients with small intercondylar area.[19]

Limitations

Several limitations of this study warrant mention. First, the number of articles that were used in the meta-analysis was relatively small, and they were mostly nonrandomized retrospective cohort studies. Due to the novel nature of this technique, there are limited randomized controlled trials investigating the use of noncircular ACLR that were available for inclusion in our analysis. Because of the paucity of large prospective comparative studies between rectangular tunnels and conventional round, there were significant limitations in the data that was able to be analyzed for meta-analysis. In addition, within those studies that were analyzed, not unlike many other meta-analyses on various ACLR techniques, the results of which should be considered in light of the variable methodologies among the included studies and lack of standardization that could potentially confound the findings as described. In addition, follow-up time varied between studies and may have influenced our results. Larger, randomized prospective studies are needed to further our understanding of the clinical efficacy of these novel techniques in ACLR.

Conclusions

Noncircular femoral tunnel ACLR has been shown to have some biomechanical advantages, including early graft healing and less tunnel widening, as well as reasonable and comparable clinical outcomes. Studies have demonstrated improved rotational stability due to the flatter shape of the graft and improved Lysholm scores in comparison to the conventional round femoral tunnel ACLR. The smaller surface area of the graft makes this operation desirable particularly in patients with a small intercondylar area and in some revision, cases allowing the creation of the tunnel in a more anatomic position.

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Conflicts of interest

There are no conflicts of interest.

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