A Comprehensive Meta-analysis of Clinical and Biomechanical Outcomes Comparing Double-Bundle and Single-Bundle Posterior Cruciate Ligament Reconstruction Techniques

CME

Suhas P. Dasari,* MD, Alec A. Warrier,* BS, Joshua J. Condon,* BS, Enzo S. Mameri,* MD, Zeeshan A. Khan,* BA, Benjamin Kerzner,* BS, Safa Gursoy,* MD, PhD, Hasani W. Swindell,* MD, Mario Hevesi,* MD, PhD, and Jorge Chahla,*† MD, PhD
Investigation performed at the Department of Orthopaedic Surgery, Rush University Medical Center, Chicago, Illinois, USA

Background: Posterior cruciate ligament (PCL) reconstruction techniques have historically focused on single-bundle (SB) reconstruction of the larger anterolateral bundle without addressing the codominant posteromedial bundle. The SB technique has been associated with residual laxity and instability, leading to the development of double-bundle (DB) reconstruction techniques.

Purpose: To perform a meta-analysis of comparative clinical and biomechanical studies to differentiate the pooled outcomes of SB and DB PCL reconstruction cohorts.

Study Design: Meta-analysis and systematic review: Level of evidence, 3.

Methods: Six databases were queried in February 2022 for literature directly comparing clinical and biomechanical outcomes for patients or cadaveric specimens undergoing DB PCL reconstruction against SB PCL reconstruction. Biomechanical outcomes included posterior tibial translational laxity, external rotational laxity, and varus laxity at 30° and 90° of knee flexion. Clinical outcomes included the side-to-side difference in posterior tibial translation during postoperative stress radiographs, risk of a major complication, and the following postoperative patient-reported outcome measures: Lysholm, Tegner, and International Knee Documentation Committee (IKDC) subjective and objective scores. A random-effects model was used to compare pooled clinical and biomechanical outcomes between the cohorts.

Results: Fifteen biomechanical studies and 13 clinical studies were included in this meta-analysis. The DB group demonstrated significantly less posterior tibial translation at 30° and 90° of knee flexion ($P < .00001$). Additionally, the DB group demonstrated significantly less external rotation laxity at 90° of knee flexion ($P = .0002$) but not at 30° of knee flexion ($P = .33$). There was no difference in varus laxity between the groups at 30° ($P = .56$) or 90° ($P = .24$) of knee flexion. There was significantly less translation on stress radiographs in the DB group ($P = .02$). Clinically, there was no significant difference between the groups for the Lysholm score ($P = .95$), Tegner score ($P = .14$), or risk of a major complication ($P = .93$). DB PCL reconstruction led to significantly higher odds of achieving ''normal'' or ''near normal'' objective IKDC outcomes for the included prospective studies ($P = .04$) and higher subjective IKDC scores ($P = .01$).

Conclusion: DB PCL reconstruction leads to superior biomechanical outcomes and clinical outcomes relative to SB PCL reconstruction. Re-creating native anatomy during PCL reconstruction maximizes biomechanical stability and clinical outcomes.

Keywords: posterior cruciate ligament; PCL; double-bundle reconstruction; single-bundle reconstruction; posteromedial bundle

The posterior cruciate ligament (PCL) is composed of 2 distinct codominant bundles: the larger anterolateral bundle (ALB) and the smaller posteromedial bundle (PMB) (Figure 1).[9,36] Despite the presence of these 2 separate anatomic bundles, PCL reconstruction techniques have historically focused on single-bundle (SB) reconstruction of the larger ALB without addressing the smaller PMB. Failure to properly address both bundles can lead to impaired stability of the knee joint.[40] Recent studies have suggested that patients undergoing SB reconstruction will continue to demonstrate residual posterior tibial translation on stress radiographs, as well as posterior and rotational tibial instability on examination.[5,30,40]

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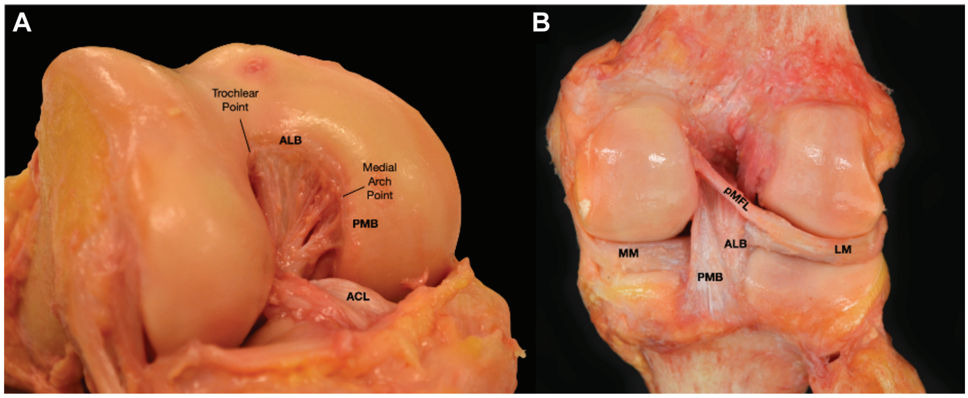

Figure 1. Anatomic dissection of the knee demonstrating the codominant anterolateral bundle (ALB) and posteromedial bundle (PMB) of the posterior cruciate ligament. (A) The trochlear point and medial arch point can be seen as well as the anterior cruciate ligament (ACL). (B) The medial meniscus (MM), lateral meniscus (LM), and posterior meniscofemoral ligament can also be appreciated (pMFL).

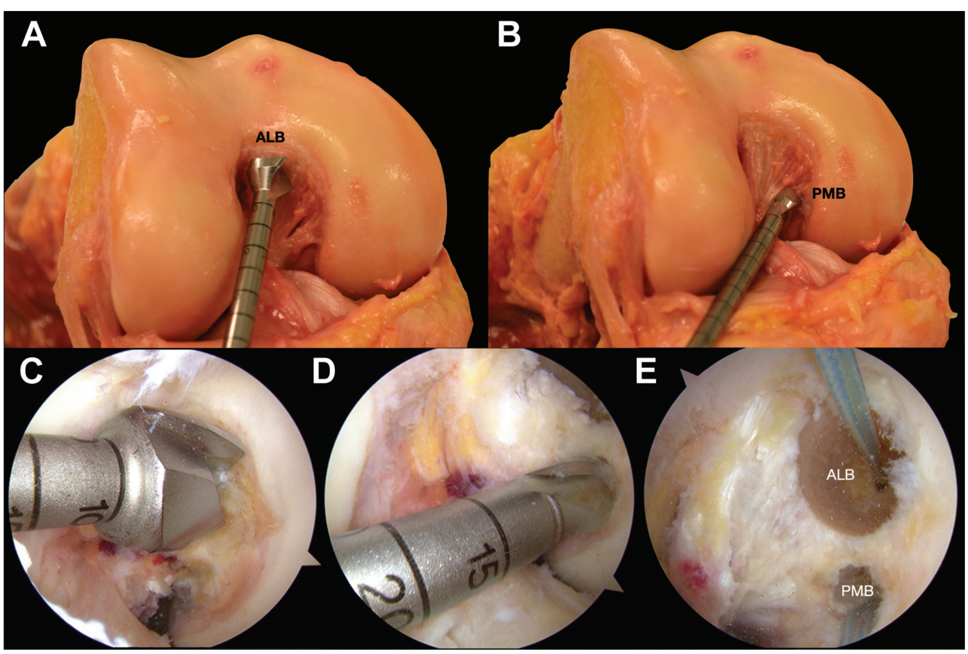

Figure 2. Double-bundle PCL reconstruction as seen in cadaveric specimen demonstration (A, B) and arthroscopic images (C-E). (A, C) The correct anatomic position for drilling of the anterolateral bundle femoral tunnel and (B, D) the same for the posteromedial bundle. (E) Arthroscopic visualization via the anterolateral portal of the femoral tunnels for double-bundle PCL. ALB, anterolateral bundle; PCL, posterior cruciate ligament; PMB, posteromedial bundle.

†Address correspondence to Jorge Chahla, MD, PhD, Department of Orthopaedic Surgery, Rush University Medical Center, 1611 W Harrison St, Suite 300, Chicago, IL 60612 USA (email: jorge.chahla@rushortho.com).

*Department of Orthopaedic Surgery, Rush University Medical Center, Chicago, Illinois, USA.

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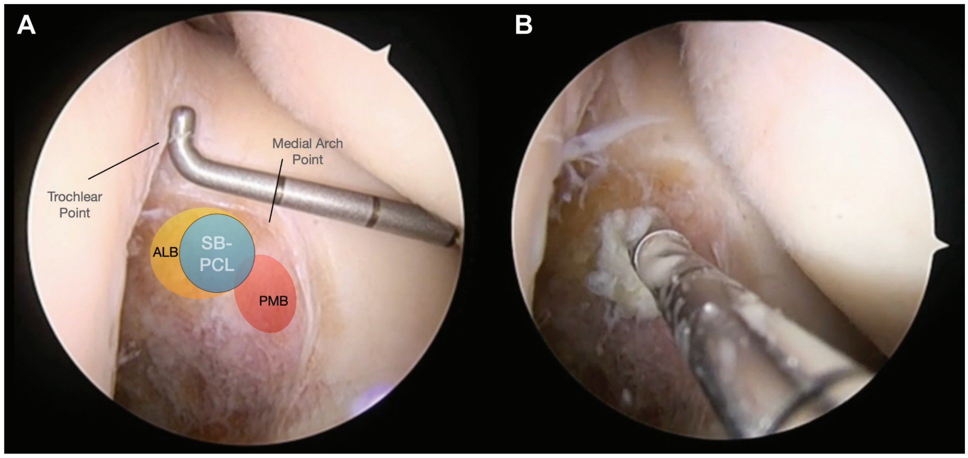

Figure 3. Single-bundle (SB) posterior cruciate ligament (PCL) reconstruction as seen in arthroscopic visualization via the anterolateral portal. (A) The anterolateral and posteromedial bundle footprints of the PCL, as well as the typical placement of the SB femoral tunnel are illustrated. (B) Guide pin drilling for the SB tunnel is typically placed at the anterior and distal portion of the anterolateral bundle footprint, on the anterior border of the remnant fibers, 7 mm from the distal cartilage border and at the 1-o'clock position for the right knee (or 11-o'clock for the left knee). ALB, anterolateral bundle; PMB, posteromedial bundle; SB, single bundle.

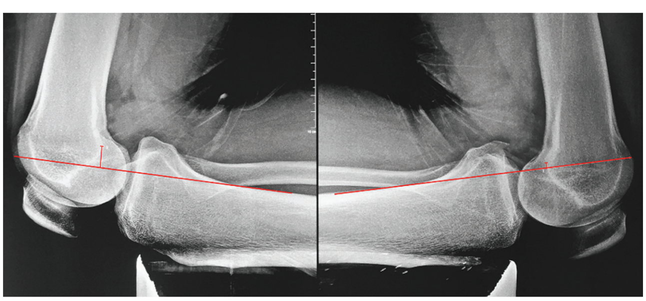

Figure 4. Bilateral kneeling stress radiographs for the objective evaluation of posterior knee laxity. A padded surface supports the legs, from the tibial tubercle to the distal tibia, while the patella and femur are unsupported with the knee at approximately 90° of flexion. A line along the posterior tibial cortex is drawn, and the perpendicular distance to the farthest posterior point of the Blumensaat line is measured for comparison with the intact contralateral knee.

Kennedy et al[22,23] demonstrated a codominant functional relationship between the ALB and PMB over a full range of knee flexion angles. This codominant functional relationship between the bundles makes it challenging to adequately restore normal kinematics of the knee with SB reconstruction alone and prompted the development of the double-bundle (DB) PCL reconstruction technique to address PCL insufficiency.[49] In this technique, the native PCL is reconstructed utilizing 2 femoral tunnels and a single tibial tunnel to re-create the ALB and PMB to restore the native anatomy and biomechanics of the knee joint (Figures 2 and 3).[5,7,37,38] The initial clinical outcomes of DB PCL reconstruction have been promising with 2 randomized controlled trials showing improved in vivo stability with the DB technique relative to the SB technique.[30,53] Biomechanical studies have consistently found superior outcomes with the DB reconstructive technique relative to SB techniques, but the clinical effect of this biomechanical benefit has remained controversial to date.[‡]

Therefore, the purpose of this study was to perform a comprehensive systematic review and meta-analysis of clinical studies and biomechanical cadaveric studies directly comparing outcomes between DB PCL reconstruction and SB PCL reconstruction. We hypothesized that DB PCL reconstruction would demonstrate superior biomechanical outcomes when pooling cadaveric data performed in a controlled laboratory setting and that DB PCL reconstruction would yield superior pooled subjective and objective patient outcomes in the clinical setting.

METHODS

Article Identification and Selection

The study was conducted in accordance with the 2020 PRISMA (Preferred Reporting Items for Systematic Reviews and Meta-Analyses) statement.[41] The Cochrane Database of Systematic Reviews, the Cochrane Register of Controlled Trials, PubMed, MEDLINE, Web of Science, and SCOPUS were queried in February 2022 for literature comparing the biomechanical and clinical outcomes for patients or cadaveric knee specimens that underwent an SB or DB PCL reconstruction. The following search terms were used: "posterior cruciate ligament" AND "bundle" OR "PCL" AND "bundle." The inclusion criteria were as follows: (1) either a biomechanical study that utilized cadaveric specimens or a clinical study with kinematic outcomes,

‡References 5-7, 12, 16, 26, 27, 29, 30, 53, 54.

radiographic outcomes, and/or patient-reported outcome measures; (2) direct comparison of SB and DB PCL reconstruction; (3) clinical studies with a level of evidence 1, 2, or 3; (4) biomechanical studies that utilized cadaveric human knee specimens in a controlled laboratory setting; and (5) English language. Exclusion criteria were as follows: (1) single-arm noncomparative studies and (2) any animal study, editorial article, survey, letter to the editor, special topic, or expert review. Two investigators (A.A.W. and J.J.C.) independently screened articles by title, abstract, and full text, when appropriate. For any disagreements, these 2 authors discussed the study, and a consensus decision was made.

Outcome Measures and Data Extraction

The primary biomechanical outcome measures evaluated in this meta-analysis were (1) posterior tibial translational laxity in the controlled laboratory setting at 30° and 90° of knee flexion, (2) external rotational laxity in the controlled laboratory setting at 30° and 90° of knee flexion, and (3) varus laxity in the controlled laboratory setting at 30° and 90° of knee flexion. The primary clinical outcome measures evaluated in this meta-analysis were (1) the side-to-side difference in posterior tibial translation during postoperative stress radiographs (Figure 4); (2) postoperative Lysholm scores; (3) postoperative Tegner scores; (4) postoperative International Knee Documentation Committee (IKDC) subjective scores; (5) postoperative IKDC objective scores; and (6) major complications, which were defined as severe restriction of range of motion (ROM), ROM deficit as defined by the respective authors, postoperative failure as defined by the respective authors, requirement of additional surgery, and tunnel collapse as defined by femoral fracture between separate drilled tunnels in DB PCL reconstructions. A customized data extraction spreadsheet was created to record all relevant data from the included studies: publication information, study design, level of evidence, demographic information (age, sex, donor age), time from injury to surgery, time at final follow-up, concomitant injuries, postoperative rehabilitation, the aforementioned primary outcomes of this study, and the surgical technique (graft type, positioning, and fixation). Before inclusion, all data were qualitatively analyzed by their methods, results, discussion, and conclusion. For any study where the data were not explicitly reported in the text or tables, data were extracted from the previous meta-analyses by Chahla et al,[5] Lee et al,[29] and Krott et al.[26] If the study was not in one of these meta-analyses, then values were approximated from the figures. For values reported as median and range, the mean and standard deviation were approximated using the methods described by Hozo et al.[19]

Risk of Bias Assessment

Two investigators (A.A.W. and J.J.C.) independently assessed the risk of bias of nonrandomized clinical studies using the methodological index for nonrandomized studies (MINORS) criteria.[45] In summary, the numerical scale is composed of 12 questions for nonrandomized studies. Items are scored 0 for not reported, 1 for reported but inadequate, and 2 for reported and adequate. For a comparative study, an ideal score would be 24 points. For randomized studies, the Cochrane risk of bias tool was implemented.[46] Domains assessed include bias arising from the randomization process, deviations from the intended intervention, missing outcome data, measurement of the outcome, and selection of the reported result. The domains were assessed as having high, some, or low concern for bias. The risk of bias of the biomechanical studies was assessed using the Quality Appraisal for Cadaveric Studies (QUACS) scale.[51] In summary, the QUACS bias analysis tool is composed of 13 components that are graded 1 for yes/present and 0 for no/absent. An ideal score would be 13 points, and a score $\geq$10 is indicated as low risk of bias.[27] Any disagreement between the investigators was resolved by review of a third investigator (Z.A.K.).

Statistical Analysis

A random-effects model was chosen by the variable design of the studies and the methodology used for sampling the data.[4] Weighted mean differences (WMDs) and 95% CIs were used to assess the mean and range of true means for each continuous numerical outcome measure based on the studies. For continuous numerical outcomes, an inverse variance model was used. For the postoperative IKDC objective score, a pooled odds ratio (OR) with a 95% CI was used to compare the odds of a patient being classified as "normal" or "near normal" between the reconstruction techniques. A risk difference (RD) with a 95% CI was used to compare the risk of a major complication based on the PCL reconstruction technique implemented. For dichotomous outcomes, a Mantel-Haenszel model was implemented. An alpha $<$.05 was assigned as significant. The percentage of variance in the true effect value and the percentage of variance from the sampling error were determined using I^2. Statistical analysis was performed using Review Manager 5 (Nordic Cochrane Center) and IBM SPSS Statistics (Version 28.0).

RESULTS

Study Selection

A total of 28 studies (15[§] biomechanical and 13 clinical[||]) met the inclusion/exclusion criteria and were included in this investigation (Figure 5). Among the 15 biomechanical studies, 2 did not report data in a fashion that could be included in a formal meta-analysis.[33,35] Furthermore, the data for these studies were not in the previous meta-analysis of biomechanical PCL reconstruction outcomes.[29] As a result, of the 15 biomechanical studies included for

[§]References 1-3, 15, 16, 22, 23, 33-35, 37, 38, 42, 48, 50.
[||]References 11, 14, 17, 21, 24, 25, 30, 44, 47, 52-54.

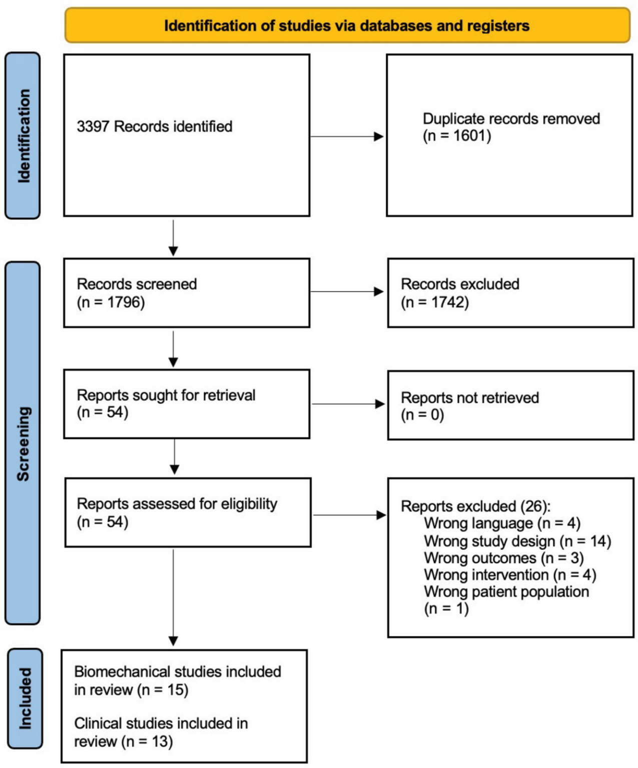

Figure 5. PRISMA (Preferred Reporting Items for Systematic Reviews and Meta-Analyses) flowchart.

qualitative assessment in the present systematic review, only 13 had quantitative data in formal meta-analysis. Kim et al[25] compared the transtibial SB technique, arthroscopic inlay SB technique, and arthroscopic inlay DB technique. This study was included in the present meta-analysis as 2 separate studies, which is consistent with methodology used in previous meta-analyses.[5,26] Additionally, a study by Kennedy et al[22,23] was divided into a part 1 and part 2 component but tested the SB and DB groups in the same experimental setting. This study was considered a single study within the present meta-analysis, which is consistent with a previous meta-analysis.[29]

Study Characteristics and Demographics

All 15 biomechanical studies were controlled laboratory studies performed on fresh-frozen human cadaveric knee specimens. Among the 13 comparative clinical studies, 8 were nonrandomized retrospective studies, 2 were nonrandomized prospective studies, and 3 were randomized controlled trials. Among the 15 biomechanical studies, there were 129 cadaveric specimens treated with DB PCL reconstruction and 129 treated with SB PCL reconstruction (Table 1). The weighted mean of the donor age for the specimens in this meta-analysis was 59.4 years (range, 35.1-78). The 13 clinical studies consisted of 275 patients with a mean age of 29.4 years (range, 23.5-36.0) who were treated with a DB PCL reconstruction technique at final follow-up and 320 patients with a mean age of 30.6 years (range, 25.1-34.0) who were treated with an SB PCL reconstruction technique at final follow-up (Table 2). The weighted mean final follow-up was 40.9 months (range, 10.4-150).

Literature Quality Assessment

Bias analysis of the 15 biomechanical studies was performed using the QUACS bias analysis tool (Appendix Figure A1, available in the online version of this article). The mean score was 9.5 (range, 6-12). Among the 13 clinical studies, there were 10 nonrandomized comparative studies assessed with the MINORS tool (Appendix Figure A2) and 3 randomized controlled trials assessed with the Cochrane risk of bias tool (Appendix Figure A3). For the nonrandomized comparative studies, the mean MINORS score was 18.5 (range, 14-22). There were 2 prospective nonrandomized clinical studies and 8 retrospective nonrandomized clinical studies in this meta-analysis. Bias assessment of the 3 randomized controlled trials was performed using the Cochrane risk of bias tool. There was low concern for bias among these 3 studies.

Surgical Technique and Postoperative Rehabilitation

There was relative heterogeneity with respect to surgical technique for the clinical and biomechanical studies. All in vitro and in vivo DB techniques implemented a single common tibial fixation location except for a randomized controlled trial by Li et al,[30] where the authors utilized 2 tibial tunnels. This clinical investigation by Li et al was included in the present meta-analysis to remain consistent with the previous meta-analyses by Chahla et al,[5] Zhao et al,[55] and Krott et al,[26] which had all included this randomized controlled trial in their studies.

It is important to note that there was substantial variation in regard to graft choice, size, positioning, and fixation device for the SB and DB techniques of the studies. For example, Achilles tendon grafts and patellar tendon grafts were the most commonly implemented grafts in the biomechanical studies; however, there was variation in graft choice among the studies with reported implementation of gracilis with semitendinosus tendon, tibialis anterior tendon, and tibialis posterior tendon. This variation was also noted among the clinical studies, for which the Achilles tendon was the most typically used. Like graft choice, there was similar variation with regard to specific fixation devices and angles used across the techniques. The biomechanical studies most often used interference screws, titanium and biocomposite, for femoral fixation, followed by custom-made fixation devices, cylindrical stainless-steel bone grips, and titanium EndoButtons. For tibial fixation, cortical screws and washers were most often utilized, with cancellous screws, custom fixation devices, and bone cement augmentation being implemented to a lesser extent. Clinical studies demonstrated similar variation in fixation technique. Bioabsorbable interference screws and EndoButtons were most often used for femoral fixation. For tibial fixation, interference screws were nearly always

TABLE 1
Study Characteristics and Demographic Information of the Included Biomechanical Studies[a]

Study (Year)[b]	Technique	No. of Specimens (M:F)	Donor Age, y	Biomechanical Outcomes Tested
Guo[15] (2018)	SB	7 (NR)	<60	Posterior tibial translation, external rotation
	DB	7 (NR)	<60	laxity (dial test), varus laxity
Nuelle[38] (2017)	SB	4 (NR)	NR	Posterior tibial translation
	DB	4 (NR)	NR	
Milles[37] (2017)	SB	4 (NR)	NR	Posterior tibial translation
	DB	4 (NR)	NR	
Kennedy[22,23,c] (2014-2013)	SB	9 (6:3)	52.3	Posterior tibial translation, external rotation
	DB	9 (6:3)	52.3	laxity (dial test)
Wijdicks[49] (2013)	SB	9 (5:4)	54.8	Posterior tibial translation, external rotation
	DB	9 (5:4)	54.8	laxity (dial test), varus laxity
Markolf[35] (2010)	SB	10 (NR)	35.1	Posterior tibial translation
	DB	10 (NR)	35.1	
Whiddon[48] (2008)	SB	9 (5:4)	71	Posterior tibial translation, external rotation
	DB	9 (5:4)	71	laxity (dial test)
Apsingi[1] (2008)	SB	9 (6:3)	72	Posterior tibial translation, external rotation
	DB	9 (6:3)	72	laxity (dial test), varus laxity
Apsingi[2] (2008)	SB	10 (6:4)	78	Posterior tibial translation, external rotation
	DB	10 (6:4)	78	laxity (dial test), varus laxity
Markolf[34] (2006)	SB	13 (NR)	38.4	Posterior tibial translation
	DB	13 (NR)	38.4	
Wiley[50] (2006)	DB	8 (5:3)	73	Posterior tibial translation, external rotation
	DB	8 (5:3)	73	laxity (dial test), varus laxity
Bergfeld[3] (2005)	SB	8 (4:4)	48.5	Posterior tibial translation
	DB	8 (4:4)	48.5	
Mannor[33] (2000)	SB	11 (7:4)	77.2	Posterior tibial translation
	DB	11 (7:4)	77.2	
Harner[16] (2000)	SB	10 (NR)	39-73[d]	Posterior tibial translation
	DB	10 (NR)	39-73[d]	
Race[42] (1998)	SB	8 (NR)	60	Posterior tibial translation
	DB	8 (NR)	60	

[a]DB, double bundle; F, female; M, male; NR, not reported; SB, single bundle.
[b]Each study design: controlled laboratory testing of fresh-frozen human cadaveric specimens.
[c]Parts 1 and 2.
[d]Range.

used, with few studies implementing staples, suture washers, or cancellous screws. Fixation angle among biomechanical and clinical techniques had similar variation, but most angles for the SB technique or ALB of the DB technique ranged from 70° to 90° of flexion, within the parameters recommended in current literature.[8,22] Detailed information regarding the surgical techniques for the biomechanical studies and clinical studies are presented in Appendix Tables A1 and A2 (available online).

There was variation in the postoperative rehabilitation protocols implemented for the clinical studies. All but 1[17] of the studies clearly stated the use of a postoperative brace. A detailed summary of the postoperative rehabilitation protocols and postoperative braces used in the studies is summarized in Appendix Table A3 (available online).

Biomechanical Outcomes

Posterior Tibial Translational Laxity. Twelve studies reported on posterior tibial translational laxity at 30° of knee flexion (Figure 6, top). There were 99 cadaveric knees tested with an SB reconstruction technique and 97 specimens tested with a DB reconstruction technique. There was significantly lower posterior tibial translation (WMD, 1.26 mm) in the specimens that underwent DB reconstruction versus SB reconstruction (95% CI, 0.76-1.75; $P < .00001$). Thirteen studies examined posterior tibial translational laxity at 90° of knee flexion (Figure 6, bottom). For both reconstruction groups, 108 specimens were examined for a total of 216 cadaveric knees. There was significantly lower posterior tibial translation (WMD, 1.58 mm) in the specimens that underwent DB reconstruction relative to the SB reconstruction group (95% CI, 0.96-2.19; $P < .00001$).

External Rotation Laxity. Six studies reported on laxity when an external rotation force was applied at 30° of knee flexion (Figure 7, top). There were 52 cadaveric knees tested in each reconstruction group for a total of 104 specimens. While the DB group had less external rotatory laxity than the SB group, this difference was not significant at 30° of knee flexion (WMD, 1.05; 95% CI, –1.07 to 3.18; $P = .33$). When external rotation laxity was examined at 90° of knee flexion, 7 studies compared the relative resistance provided by SB and DB PCL reconstruction techniques (Figure

TABLE 2
Study Characteristics and Demographic Information of the Included Clinical Studies[a]

Study (Year)	LoE	Study Design	Technique	No. of Patients (M:F)	Mean Age, y	Final Follow-up, mo	Time From Injury to Surgery, mo	Concomitant Injuries	Objective and Subjective Outcomes
Xu[52] (2019)	2	Prospective cohort	SB	60 (42:18)	33.6	28	4.5	Meniscal tear: 10; cartilage injury: 11	ROM, Lysholm
			DB	30 (22:8)	31.5	28	5	Meniscal tear, 6; cartilage injury, 5	
Yoon[54] (2019)	3	Retrospective cohort	SB	28 (22:6)	29.1	10.4	10.2	Medial meniscus, 4; lateral meniscus, 2; cartilage injury, 5	Stress radiography with Telos, Lysholm, Tegner, IKDC
			DB	36 (33:3)	27	10.9	9.8	Medial meniscus, 3; lateral meniscus, 2; cartilage injury, 4	
Jain[21] (2016)	3	Retrospective cohort	SB	22 (22:0)	26.4	28.2	3.4	None	Stress radiography, KT1000, posterior drawer, Lysholm, IKDC
			DB	18 (18:0)	27.44	28.2	3.8	None	
Deie[11] (2015)	3	Retrospective cohort	SB	27 (18:9)	34	150	NR	ACL, 1; MCL, 4; PLC, 4	Lysholm
			DB	13 (11:2)	32	150	NR	ACL, 1; MCL, 2; PLC, 3	
Li[30] (2014)	2	Randomized controlled trial	SB	22 (15:7)	25.1	28.7	1.9	None;	KT1000, Lysholm, Tegner, IKDC
			DB	24 (18:6)	23.5	30.4	1.5	None	
Fanelli[12] (2012)	3	Retrospective cohort	SB	45 (NR)	NR	24-72	NR	ACL, collateral ligament	Stress radiography with Telos, KT1000, Lysholm, Tegner
			DB	45 (NR)	NR	46.4	NR	ACL, collateral ligament	
Kim[24] (2011)	3	Retrospective cohort	SB	23 (19:4)	30.7	51.2	11.2	PLC reconstruction, partial meniscectomies	Stress radiography with Telos, Lysholm, IKDC
			DB	19 (15:4)	31.3	44.5	12.7	PLC, all patients; lateral meniscus, 1; medial meniscus, 1	
Yoon[53] (2011)	2	Randomized controlled trial	SB	25 (20:5)	28.5	31	37	Medial meniscus, 4; lateral meniscus, 2; cartilage injury, 5	Stress radiography with Telos, ROM, Lysholm, Tegner, IKDC
			DB	28 (25:3)	27.4	33	35	Medial meniscus, 3; lateral meniscus, 2; cartilage injury, 4	
Shon[44] (2010)	3	Retrospective cohort	SB	14 (11:3)	34	90.5	11.3	Meniscal injury, 2; chondromalacia (grade II), 2	Stress radiography with Telos, posterior drawer, Lysholm, Tegner
			DB	16 (15:1)	36	64	7.1	Meniscal injury, 1; chondromalacia III of PFJ, 2	
Kim[25] AI (2009)	3	Case-control	SB	11 (8:3)	31.9	36.3	9.4	None	Stress radiography, ROM, Lysholm
			DB	10 (7:3)	33.6	29.4	9.4	None	
Kim[25] TT (2009)	3	Case-control	SB	8 (5:3)	32.4	46.4	9.4	None	Stress radiography, ROM, Lysholm
			DB	NA	NA	NA	NA	NA	
Hatayama[17] (2006)	3	Retrospective cohort	SB	10 (7:3)	29.6	24	NR	ACL, 2; MCL, 2; LCL, 2	Stress radiography, IKDC
			DB	10 (7:3)	34.5	24	NR	ACL, 2; ACL and MCL, 2; LCL, 1	
Houe[18] (2004)	2	Prospective cohort	SB	6 (NR)	31[b]	35[b]	>6	None	Lysholm, Tegner
			DB	10 (NR)	31[b]	35[b]	>6	None	
Wang[47] (2004)	2	Randomized controlled trial	SB	19 (14:5)	29.4	41	8.5	Femur fractures, 2; tibia fracture, 1; meniscal tears, 4	KT1000, posterior drawer, reverse Lachman, Lysholm, Tegner, IKDC
			DB	16 (12:4)	28.2	28.2	6.5	Chondral injury, 1; meniscal tears, 3	

[a]ACL, anterior cruciate ligament; AI, arthroscopic inlay; DB, double bundle; F, female; IKDC, International Knee Documentation Committee; LoE, level of evidence; LCL, lateral collateral ligament; M, male; MCL, medial collateral ligament; NA, not applicable; NR, not reported; PFJ, patellofemoral joint; PLC, posterolateral corner; ROM, range of motion; SB, single bundle; TT, transtibial.

[b]Median.

# of patients at final follow-up

7, bottom). At 90° of knee flexion, DB PCL reconstruction had significantly higher resistance to external rotation forces at the knee relative to the SB PCL reconstruction group. This difference was statistically significant with a WMD of 1.36° (95% CI, 0.64 to 2.09; P = .0002).

Varus Laxity. Five studies reported on resistance to varus forces at 30° (Figure 8, top) and 90° (Figure 8, bottom) of knee flexion. At both knee flexion angles, there were 43 specimens treated with SB reconstruction and 43 specimens treated with DB reconstruction. There was no

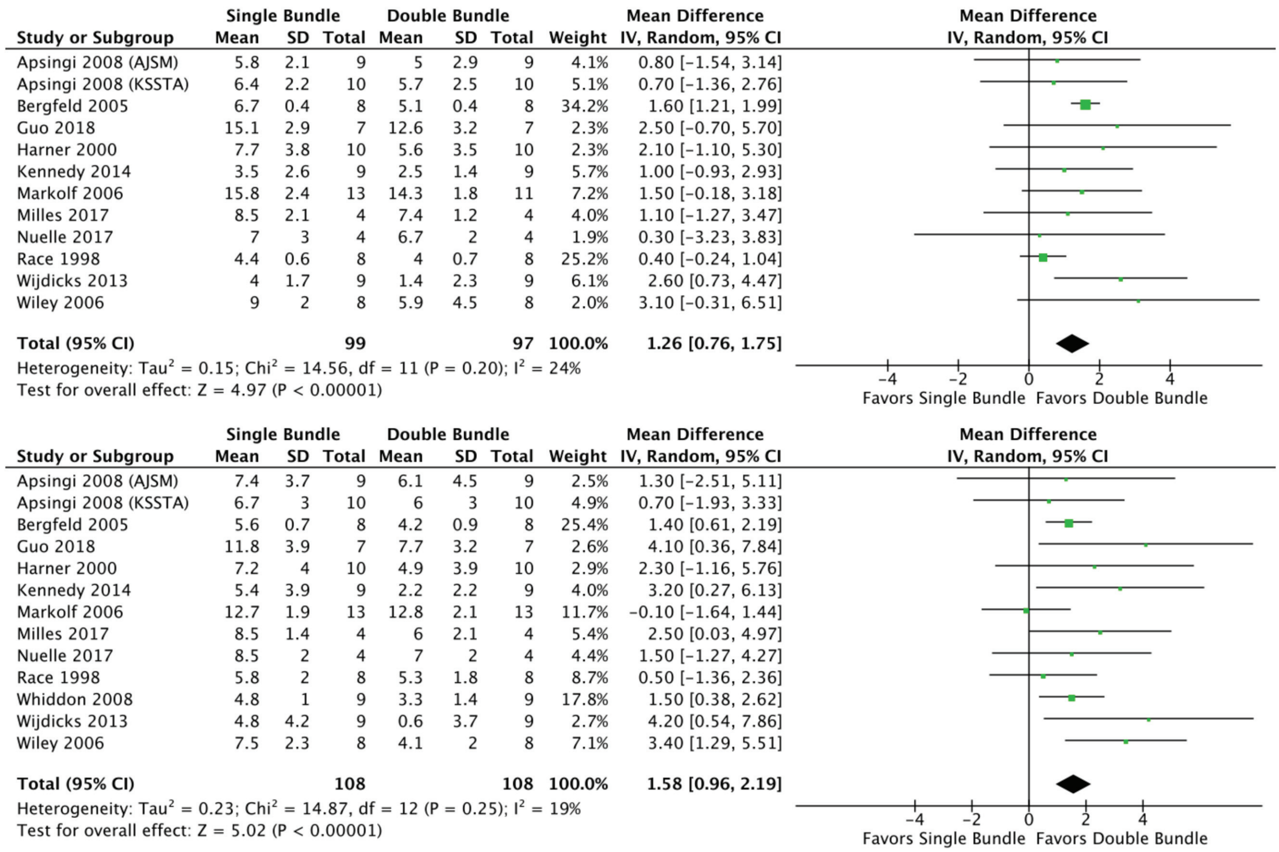

Figure 6. Forest plot demonstrating the weighted mean difference for posterior tibial translation (in mm) of single- and double-bundle posterior cruciate ligament reconstruction techniques in a controlled laboratory setting with cadaveric human knees at 30° (top) and 90° (bottom) of flexion. This includes a summary estimate (center of the diamond) and a 95% CI (width of the diamond) for the true mean difference. The size of each square represents the relative weight given to each study. *AJSM*, *American Journal of Sports Medicine; KSSTA*, *Knee Surgery, Sports Traumatology, Arthroscopy*; IV, inverse variance.

difference between the groups at 30° (WMD, 0.11; 95% CI, −0.25 to 0.47; P = .56) or 90° (WMD, 0.50; 95% CI, −0.33 to 1.33; P = .24) of knee flexion.

Clinical Outcomes

Stress Radiographs. Eight studies measured the side-to-side difference in posterior tibial translational laxity using stress radiographs in the clinical setting (Figure 9). A total of 174 patients treated with a DB PCL reconstruction and 165 patients treated with an SB PCL reconstruction were in the subsequent analysis. For this outcome measure, the DB group had significantly lower side-to-side differences in posterior tibial translational laxity relative to the SB group, with a WMD of 0.49 mm (95% CI, 0.07-0.91; P = .02).

Lysholm. Thirteen studies reported postoperative Lysholm scores for patients treated with a DB or SB PCL reconstruction (Figure 10). Of these 13 studies, 5 were prospective and 8 were retrospective comparative studies. For this outcome, 272 patients treated with a DB PCL reconstruction procedure and 311 patients treated with an SB PCL reconstruction procedure were in subsequent analysis. There was no difference between the groups for postoperative Lysholm scores (WMD, −0.07; 95% CI, −1.98 to 1.85; P = .95).

Tegner. Seven studies reported postoperative Tegner scores for 169 patients treated with an SB PCL reconstruction technique and 175 patients treated with a DB PCL reconstruction technique (Figure 11). Of these 7 studies, 4 were prospective and 3 were retrospective comparative studies. Pooled Tegner scores for the DB group were statistically similar to the SB group (WMD, −0.49; 95% CI, −1.14 to 0.16; P = .14).

IKDC Subjective. Three studies reported postoperative IKDC subjective scores for 75 patients treated with an SB PCL reconstruction technique and 88 patients treated with a DB PCL reconstruction technique (Figure 12). Two of these studies were prospective randomized trials while 1 study was a retrospective study. The pooled IKDC subjective scores were significantly lower for the SB group relative to the DB group, with a WMD of −3.64 (95% CI, −6.41 to −0.88; P = .01).

IKDC Objective. Six studies determined postoperative IKDC objective scores for their PCL reconstruction groups (Figure 13). Three of these studies were prospective randomized controlled trials and 3 were retrospective studies.

Study or Subgroup	Single Bundle Mean	SD	Total	Double Bundle Mean	SD	Total	Weight	Mean Difference IV, Random, 95% CI
Apsingi 2008 (AJSM)	17.9	5.4	9	17.5	5	9	11.4%	0.40 [−4.41, 5.21]
Apsingi 2008 (KSSTA)	34.7	10.9	10	32.9	9.9	10	4.5%	1.80 [−7.33, 10.93]
Guo 2018	13.8	3.1	7	14.8	4.2	7	14.3%	−1.00 [−4.87, 2.87]
Whiddon 2008	11.2	1.4	9	7.6	0.4	9	25.8%	3.60 [2.65, 4.55]
Wijdicks 2013	0.7	0.4	9	0.5	0.5	9	26.9%	0.20 [−0.22, 0.62]
Wiley 2006	2.9	2.5	8	2.4	3.8	8	17.0%	0.50 [−2.65, 3.65]
Total (95% CI)			**52**			**52**	**100.0%**	**1.05 [−1.07, 3.18]**

Heterogeneity: Tau² = 4.32; Chi² = 41.99, df = 5 (P < 0.00001); I² = 88%
Test for overall effect: Z = 0.97 (P = 0.33)

Study or Subgroup	Single Bundle Mean	SD	Total	Double Bundle Mean	SD	Total	Weight	Mean Difference IV, Random, 95% CI
Apsingi 2008 (AJSM)	19	6.1	9	18.6	4.6	9	2.1%	0.40 [−4.59, 5.39]
Apsingi 2008 (KSSTA)	32.4	10.2	10	30	10.6	10	0.6%	2.40 [−6.72, 11.52]
Guo 2018	17.4	5	7	18.4	4.7	7	2.1%	−1.00 [−6.08, 4.08]
Kennedy 2014	1.9	1.7	9	1.9	2.1	9	17.0%	0.00 [−1.77, 1.77]
Whiddon 2008	11.1	1.4	9	9	0.8	9	47.8%	2.10 [1.05, 3.15]
Wijdicks 2013	1.6	1.3	9	0.4	1.6	9	29.2%	1.20 [−0.15, 2.55]
Wiley 2006	4.7	7.2	8	4.1	6.4	8	1.2%	0.60 [−6.08, 7.28]
Total (95% CI)			**61**			**61**	**100.0%**	**1.36 [0.64, 2.09]**

Heterogeneity: Tau² = 0.00; Chi² = 5.30, df = 6 (P = 0.51); I² = 0%
Test for overall effect: Z = 3.67 (P = 0.0002)

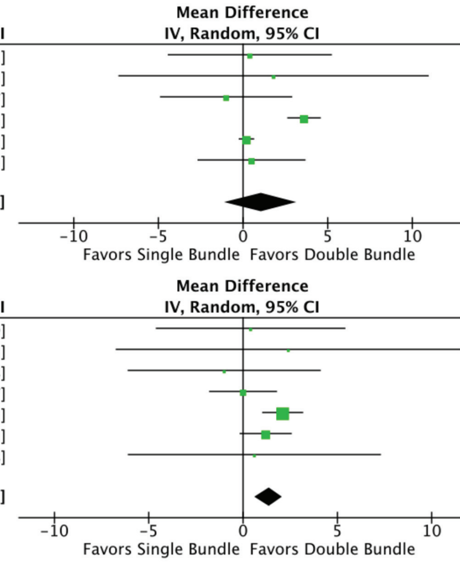

Figure 7. Forest plot demonstrating the weighted mean difference for external rotation laxity (in degrees) of single- and double-bundle posterior cruciate ligament reconstruction techniques in a controlled laboratory setting with cadaveric human knees at 30° (top) and 90° (bottom) of flexion. This includes a summary estimate (center of the diamond) and a 95% CI (width of the diamond) for the true mean difference. The size of each square represents the relative weight given to each study. *AJSM*, *American Journal of Sports Medicine; KSSTA*, *Knee Surgery, Sports Traumatology, Arthroscopy*; IV, inverse variance.

Study or Subgroup	Single Bundle Mean	SD	Total	Double Bundle Mean	SD	Total	Weight	Mean Difference IV, Random, 95% CI
Apsingi 2008 (AJSM)	3.9	2.4	9	4.1	2.2	9	2.9%	−0.20 [−2.33, 1.93]
Apsingi 2008 (KSSTA)	15.8	5.5	10	14	6.9	10	0.4%	1.80 [−3.67, 7.27]
Guo 2018	5.1	0.6	7	5	0.7	7	27.9%	0.10 [−0.58, 0.78]
Wijdicks 2013	0.3	0.3	9	0.2	0.6	9	67.7%	0.10 [−0.34, 0.54]
Wiley 2006	1.8	1.8	8	1	4.7	8	1.1%	0.80 [−2.69, 4.29]
Total (95% CI)			**43**			**43**	**100.0%**	**0.11 [−0.25, 0.47]**

Heterogeneity: Tau² = 0.00; Chi² = 0.60, df = 4 (P = 0.96); I² = 0%
Test for overall effect: Z = 0.58 (P = 0.56)

Study or Subgroup	Single Bundle Mean	SD	Total	Double Bundle Mean	SD	Total	Weight	Mean Difference IV, Random, 95% CI
Apsingi 2008 (AJSM)	4.1	2.5	9	4.1	2.2	9	14.6%	0.00 [−2.18, 2.18]
Apsingi 2008 (KSSTA)	20	7.7	10	18.2	7.7	10	1.5%	1.80 [−4.95, 8.55]
Guo 2018	7.5	1.3	7	6.8	1.4	7	34.5%	0.70 [−0.72, 2.12]
Wijdicks 2013	0.7	1.3	9	0	1.5	9	41.1%	0.70 [−0.60, 2.00]
Wiley 2006	1.3	3.6	8	2	2.1	8	8.3%	−0.70 [−3.59, 2.19]
Total (95% CI)			**43**			**43**	**100.0%**	**0.50 [−0.33, 1.33]**

Heterogeneity: Tau² = 0.00; Chi² = 1.18, df = 4 (P = 0.88); I² = 0%
Test for overall effect: Z = 1.18 (P = 0.24)

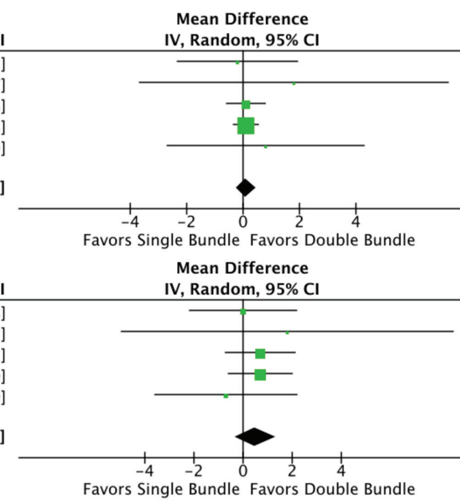

Figure 8. Forest plot demonstrating the weighted mean difference for varus laxity (in degrees) of single- and double-bundle posterior cruciate ligament reconstruction techniques in a controlled laboratory setting with cadaveric human knees at 30° (top) and 90° (bottom) of flexion. This includes a summary estimate (center of the diamond) and a 95% CI (width of the diamond) for the true mean difference. The size of each square represents the relative weight given to each study. *AJSM*, *American Journal of Sports Medicine; KSSTA*, *Knee Surgery, Sports Traumatology, Arthroscopy*; IV, inverse variance.

Of the 121 total patients who underwent SB reconstruction, 88 were classified as normal or nearly normal. Of the 114 total patients who underwent DB reconstruction, 93 were classified as normal or nearly normal. When prospective and retrospective studies were included, there was no significant difference in the odds of being classified as normal or nearly normal for the IKDC objective outcome between the groups (OR, 0.60; 95% CI, 0.31-1.14; *P* = .12). Upon further subgroup analysis, there was a significant benefit to DB reconstruction when only the prospective studies were examined. Pooled ORs from these 3 randomized controlled trials showed an increased odds of achieving normal or nearly normal IKDC objective outcomes (OR, 0.39; 95% CI, 0.16-0.95; *P* = .04).

	Single Bundle			Double Bundle				Mean Difference
Study or Subgroup	Mean	SD	Total	Mean	SD	Total	Weight	IV, Random, 95% CI
Fanelli 2012	2.56	2	45	2.36	2	45	20.6%	0.20 [−0.63, 1.03]
Hatayama 2006	3.4	4	10	4.9	2.8	10	1.9%	−1.50 [−4.53, 1.53]
Kim 2009 (AI)	4.7	1.6	11	3.6	1.4	10	9.8%	1.10 [−0.18, 2.38]
Kim 2009 (TT)	5.6	2	9	3.9	1.6	10	6.3%	1.70 [0.06, 3.34]
Kim 2011	4.2	1.7	23	3.9	1.6	19	15.1%	0.30 [−0.70, 1.30]
Shon 2010	3	1.1	14	2.8	0.5	16	30.9%	0.20 [−0.43, 0.83]
Yoon 2011	4.5	2.3	25	3.1	2.4	28	10.0%	1.40 [0.13, 2.67]
Yoon 2019	5.3	3.5	28	5	3.8	36	5.3%	0.30 [−1.49, 2.09]
Total (95% CI)			**165**			**174**	**100.0%**	**0.49 [0.07, 0.91]**

Heterogeneity: $Tau^2 = 0.05$; $Chi^2 = 8.05$, df = 7 (P = 0.33); $I^2 = 13\%$
Test for overall effect: Z = 2.26 (P = 0.02)

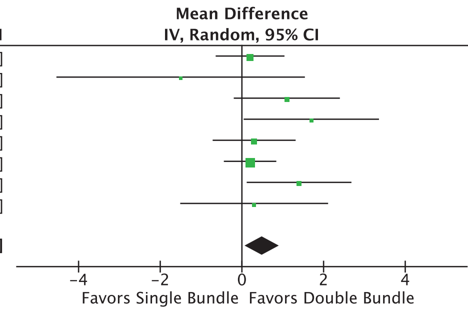

Figure 9. Forest plot demonstrating the weighted mean difference of the side-to-side difference for posterior tibial translation using stress radiographs (in mm) for patients treated with either a single- or double-bundle posterior cruciate ligament reconstruction technique. This includes a summary estimate (center of the diamond) and a 95% CI (width of the diamond) for the true mean difference. The size of each square represents the relative weight given to each study. AI, arthroscopic inlay; IV, inverse variance; TT, transtibial.

	Single Bundle			Double Bundle				Mean Difference
Study or Subgroup	Mean	SD	Total	Mean	SD	Total	Weight	IV, Random, 95% CI
4.1.1 Prospective Studies								
Houe 2004	100	1.9	16	95	2.3	10	12.0%	5.00 [3.30, 6.70]
Li 2014	88	4.2	22	89.8	3.8	24	11.1%	−1.80 [−4.12, 0.52]
Wang 2004	88	10	19	89	9	16	5.5%	−1.00 [−7.30, 5.30]
Xu 2019	90.6	5.8	59	89.8	4.9	30	11.1%	0.80 [−1.49, 3.09]
Yoon 2011	89	7.6	25	91	6	28	8.8%	−2.00 [−5.72, 1.72]
Subtotal (95% CI)			**141**			**108**	**48.5%**	**0.45 [−2.80, 3.69]**
Heterogeneity: $Tau^2 = 10.91$; $Chi^2 = 28.26$, df = 4 (P < 0.0001); $I^2 = 86\%$								
Test for overall effect: Z = 0.27 (P = 0.79)								
4.1.2 Retrospective Studies								
Deie 2015	89.1	5.6	18	91.9	4.5	10	8.7%	−2.80 [−6.60, 1.00]
Fanelli 2012	90.3	7	45	87.6	7.7	45	9.9%	2.70 [−0.34, 5.74]
Jain 2016	84.9	6	22	86.2	6.5	18	8.5%	−1.30 [−5.21, 2.61]
Kim 2009 (AI)	79.7	11.7	9	84.3	9.7	10	3.0%	−4.60 [−14.32, 5.12]
Kim 2009 (TT)	86.8	7.5	11	84.3	9.7	10	4.4%	2.50 [−4.97, 9.97]
Kim 2011	85.7	7.6	23	87.7	7.3	19	7.6%	−2.00 [−6.52, 2.52]
Shon 2010	88.1	7.3	14	88.7	9.1	16	5.9%	−0.60 [−6.47, 5.27]
Yoon 2019	73.8	18.4	28	74.4	18.4	36	3.3%	−0.60 [−9.69, 8.49]
Subtotal (95% CI)			**170**			**164**	**51.5%**	**−0.37 [−2.13, 1.38]**
Heterogeneity: $Tau^2 = 0.44$; $Chi^2 = 7.50$, df = 7 (P = 0.38); $I^2 = 7\%$								
Test for overall effect: Z = 0.42 (P = 0.68)								
Total (95% CI)			**311**			**272**	**100.0%**	**−0.07 [−1.98, 1.85]**

Heterogeneity: $Tau^2 = 7.23$; $Chi^2 = 39.57$, df = 12 (P < 0.0001); $I^2 = 70\%$
Test for overall effect: Z = 0.07 (P = 0.95)
Test for subgroup differences: $Chi^2 = 0.19$, df = 1 (P = 0.66), $I^2 = 0\%$

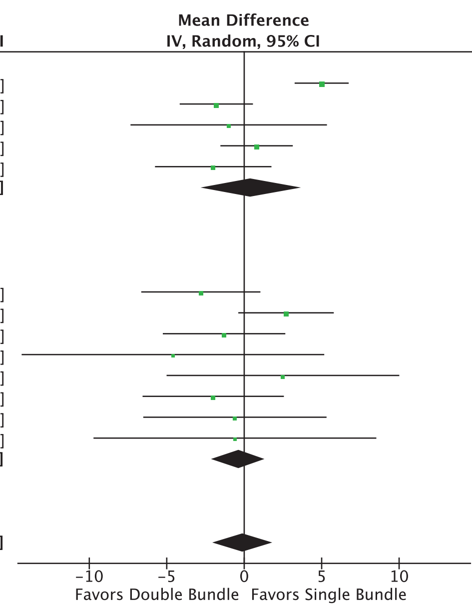

Figure 10. Forest plot demonstrating the weighted mean difference of the postoperative Lysholm score for patients treated with either a single- or double-bundle posterior cruciate ligament reconstruction technique. This includes a summary estimate (center of the diamond) and a 95% CI (width of the diamond) for the true mean difference. The size of each square represents the relative weight given to each study. The top diamond is a summary estimate of the included prospective studies. The middle diamond is a summary estimate of the included retrospective studies. The bottom diamond is a summary estimate of all included studies. AI, arthroscopic inlay; IV, inverse variance; TT, transtibial.

Major Complications. An RD was used to assess the risk of a major complication associated with the 2 reconstruction techniques (Figure 14). For this investigation, a major complication was defined as severe restriction of ROM, ROM deficit as defined by the authors, failure as defined by the authors, requirement of additional surgery, or tunnel collapse. Six studies reported the incidence of a major complication, while the remaining 7 studies did not find a major complication in either group. For the DB group, 11 of the 291 patients sustained a major complication, with 5 cases defined as postoperative failures, 1 case with tunnel collapse, and 5 cases with substantially restricted postoperative ROM as defined by the authors. For the SB group, 12 of the 333 patients sustained a major complication, with 8 cases defined as postoperative failure and 4 cases with substantially restricted postoperative ROM as defined by the authors. When the pooled RD was examined between the groups, there was no significant difference in risk (RD = 0.00; 95% CI, −0.02 to 0.03; *P* = .93).

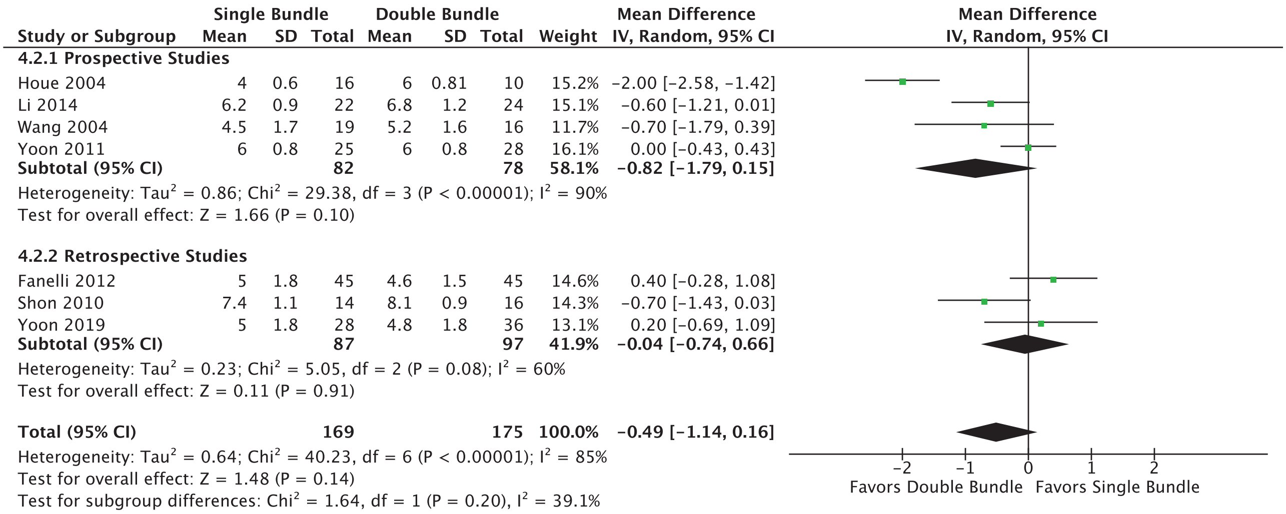

Figure 11. Forest plot demonstrating the weighted mean difference of the postoperative Tegner score for patients treated with either a single- or double-bundle posterior cruciate ligament reconstruction technique. This includes a summary estimate (center of the diamond) and a 95% CI (width of the diamond) for the true mean difference. The size of each square represents the relative weight given to each study. The top diamond is a summary estimate of the included prospective studies. The middle diamond is a summary estimate of the included retrospective studies. The bottom diamond is a summary estimate of all included studies. IV, inverse variance.

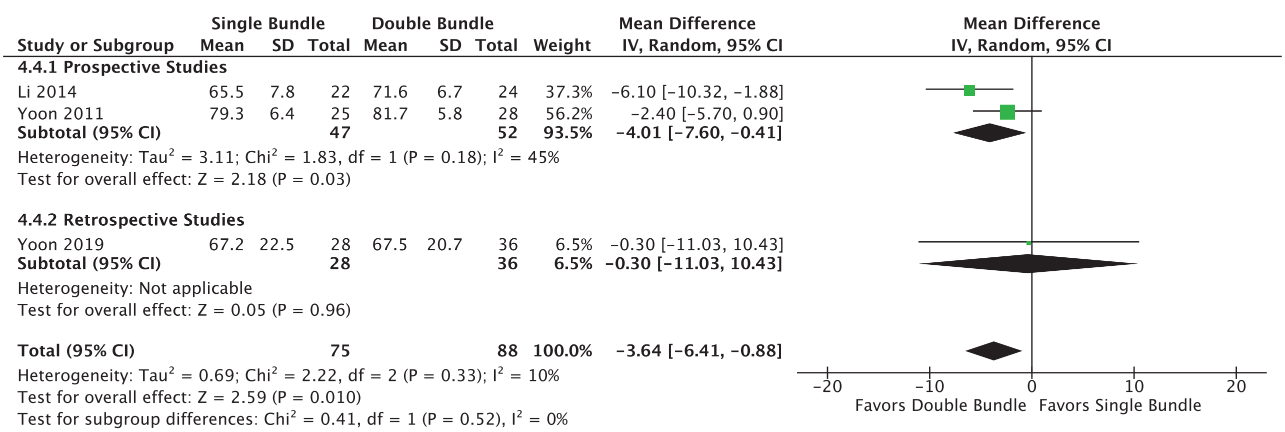

Figure 12. Forest plot demonstrating the weighted mean difference of the postoperative IKDC subjective score for patients treated with either a single- or double-bundle posterior cruciate ligament reconstruction technique. This includes a summary estimate (center of the diamond) and a 95% CI (width of the diamond) for the true mean difference. The size of each square represents the relative weight given to each study. The top diamond is a summary estimate of the included prospective studies. The middle diamond is a summary estimate of the included retrospective studies. The bottom diamond is a summary estimate of all included studies. IKDC, International Knee Documentation Committee; IV, inverse variance.

DISCUSSION

The major biomechanical findings of this investigation were as follows: (1) DB PCL reconstruction led to significantly reduced posterior tibial translation at 30° and 90° of knee flexion; (2) the DB group demonstrated significantly less external rotational laxity at 90° of knee flexion but not at 30° of knee flexion; and (3) there was no difference in varus laxity between the groups at 30° and 90° of knee flexion. The major clinical findings of this investigation were as follows: (1) DB PCL reconstruction led to significantly less in vivo posterior tibial translation on stress radiographs; (2) DB PCL reconstruction led to superior subjective IKDC clinical outcomes; (3) DB PCL reconstruction led to improved objective IKDC clinical outcomes when pooling prospective randomized controlled data, but this benefit was not maintained when including retrospective data; and (4) there was no significant difference between the groups for Lysholm scores, Tegner scores, or risk for a major complication. These results are

Study or Subgroup	Single Bundle Events	Single Bundle Total	Double Bundle Events	Double Bundle Total	Weight	Odds Ratio M-H, Random, 95% CI
4.3.1 Prospective Studies						
Li 2014	18	22	21	23	12.8%	0.43 [0.07, 2.62]
Wang 2004	11	19	13	16	17.4%	0.32 [0.07, 1.50]
Yoon 2011	18	25	24	28	22.2%	0.43 [0.11, 1.69]
Subtotal (95% CI)		**66**		**67**	**52.4%**	**0.39 [0.16, 0.95]**
Total events	47		58			
Heterogeneity: Tau² = 0.00; Chi² = 0.10, df = 2 (P = 0.95); I² = 0%						
Test for overall effect: Z = 2.08 (P = 0.04)						
4.3.2 Retrospective Studies						
Hatayama 2006	6	10	5	10	13.3%	1.50 [0.26, 8.82]
Jain 2016	19	22	16	18	11.5%	0.79 [0.12, 5.34]
Kim 2011	16	23	14	19	22.8%	0.82 [0.21, 3.16]
Subtotal (95% CI)		**55**		**47**	**47.6%**	**0.96 [0.38, 2.45]**
Total events	41		35			
Heterogeneity: Tau² = 0.00; Chi² = 0.34, df = 2 (P = 0.84); I² = 0%						
Test for overall effect: Z = 0.08 (P = 0.93)						
Total (95% CI)		**121**		**114**	**100.0%**	**0.60 [0.31, 1.14]**
Total events	88		93			
Heterogeneity: Tau² = 0.00; Chi² = 2.32, df = 5 (P = 0.80); I² = 0%						
Test for overall effect: Z = 1.56 (P = 0.12)						
Test for subgroup differences: Chi² = 1.89, df = 1 (P = 0.17), I² = 47.0%						

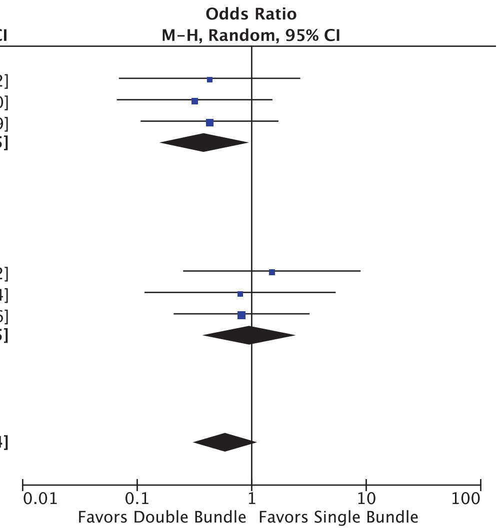

Figure 13. Forest plot demonstrating the odds ratio for PCL reconstruction patients achieving a postoperative IKDC objective score of ''normal'' or ''nearly normal.'' This includes a summary estimate (center of the diamond) and a 95% CI (width of the diamond) for the true odds ratio. The size of each square represents the relative weight given to each study. The top diamond is a summary estimate of the included prospective studies. The middle diamond is a summary estimate of the included retrospective studies. The bottom diamond is a summary estimate of all included studies. IKDC, International Knee Documentation Committee; M-H, Mantel-Haenszel.

Study or Subgroup	Single Bundle Events	Single Bundle Total	Double Bundle Events	Double Bundle Total	Weight	Risk Difference M-H, Random, 95% CI
Deie 2015	0	27	0	13	5.8%	0.00 [−0.11, 0.11]
Fanelli 2012	0	45	0	45	38.0%	0.00 [−0.04, 0.04]
Hatayama 2006	0	10	0	10	2.3%	0.00 [−0.17, 0.17]
Houe 2004	0	6	0	10	1.3%	0.00 [−0.23, 0.23]
Jain 2016	2	22	1	18	2.7%	0.04 [−0.12, 0.20]
Kim 2009 (AI)	0	11	0	10	2.4%	0.00 [−0.17, 0.17]
Kim 2009 (TT)	0	8	0	10	1.8%	0.00 [−0.19, 0.19]
Kim 2011	1	23	0	19	4.9%	0.04 [−0.08, 0.16]
Li 2014	0	25	0	25	12.3%	0.00 [−0.07, 0.07]
Shon 2010	1	14	2	16	1.5%	−0.05 [−0.26, 0.16]
Wang 2004	0	19	0	16	6.1%	0.00 [−0.11, 0.11]
Xu 2019	2	65	1	33	13.2%	0.00 [−0.07, 0.07]
Yoon 2011	1	30	2	30	5.6%	−0.03 [−0.14, 0.08]
Yoon 2019	5	28	5	36	2.1%	0.04 [−0.14, 0.22]
Total (95% CI)		**333**		**291**	**100.0%**	**0.00 [−0.02, 0.03]**
Total events	12		11			
Heterogeneity: Tau² = 0.00; Chi² = 1.51, df = 13 (P = 1.00); I² = 0%						
Test for overall effect: Z = 0.09 (P = 0.93)						

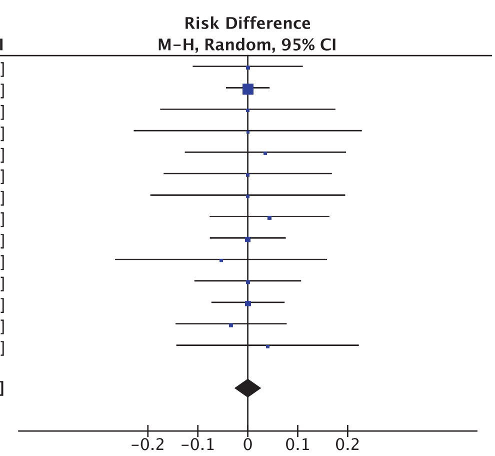

Figure 14. Forest plot demonstrating the risk difference for patients undergoing posterior cruciate ligament reconstruction with a major complication. For this investigation, a major complication was defined as severe restriction or deficit of range of motion as defined by the respective authors, failure as defined by the respective authors, requirement of additional surgery, or tunnel collapse. This includes a summary estimate (center of the diamond) and a 95% CI (width of the diamond) for the true risk difference. The size of each square represents the relative weight given to each study. AI, arthroscopic inlay; M-H: Mantel-Haenszel; TT, transtibial.

relevant in that they suggest that DB PCL reconstruction leads to improved biomechanical outcomes that translate to the in vivo setting and a statistically significant benefit to IKDC outcomes, albeit of unclear clinical significance.

SB PCL reconstruction remains the most clinically implemented PCL reconstruction technique; however, clinical and biomechanical investigations have suggested that there remains residual laxity after the procedure.[23] This is clinically significant, as residual laxity/instability can predispose patients to early degenerative osteoarthritis and poorer long-term prognosis.[16,31,43] Given these limitations of an SB reconstruction approach, the DB technique was developed. While technically challenging, DB PCL reconstruction is better able to reproduce intact in vitro knee mechanics by addressing both codominant PCL bundles.[6,7,16,22] A biomechanical investigation by Harner et al[16] demonstrated this significant biomechanical benefit of DB PCL reconstruction relative to the SB technique and reported that the DB technique effectively restored knee stability back to the intact state.

The primary biomechanical function of the PCL is to stabilize the knee joint by resisting posterior tibial translation at all flexion angles and limit rotatory instability at higher degrees of knee flexion.[27] Multiple studies have shown that isolated PCL ruptures have the greatest effect at 90° of knee flexion, suggesting that it is most important to clinically assess PCL integrity at 90° of knee flexion.[13,14,32] This is consistent with the results in this investigation. The biomechanical findings of this meta-analysis identified a significant benefit of resisting posterior tibial translation at 30° and 90° of knee flexion for the DB reconstruction group, echoing the previously described codominant functional behavior of the 2 PCL bundles. Additionally, the significant benefit in rotatory stability of the DB PCL reconstruction was demonstrated at 90° of knee flexion but not at 30° of knee flexion. Kennedy et al[23] reported that the PMB provided the majority of rotational control at increased degrees of knee flexion, which supports the improved relative rotatory stability observed in the DB group when the knee was flexed for our study.[27] Last, there was no significant difference between the techniques when addressing varus laxity. The PCL's role in resisting varus laxity is less pronounced in the intact knee than its role in rotatory and translational stability. The posterolateral corner is the primary restraint to varus rotation, and a recent meta-analysis by Lee et al[28] revealed that PCL reconstruction alone, regardless of technique, is unable to restore varus stability when the posterolateral corner is also deficient. As a result, it is possible that there was no significant pooled benefit to the DB group in this meta-analysis because the majority of biomechanical studies utilized specimens with an intact posterolateral corner.

While the present study found a significant biomechanical benefit to DB PCL reconstruction versus SB PCL reconstruction, it is important to place the pooled in vitro biomechanical results of this meta-analysis in the proper clinical context. Over the past decade, there has been a similar interest in DB anterior cruciate ligament (ACL) reconstruction, where studies had demonstrated a biomechanically significant benefit to the DB ACL reconstruction technique relative to SB ACL reconstruction, which failed to translate clinically when pooling randomized controlled data.[10,39] It is critical to note that SB ACL reconstruction, DB ACL reconstruction, and DB PCL reconstruction all restored stability to a level similar to the intact native ACL/PCL state, while SB PCL reconstruction was unable to restore stability to the native state in the controlled laboratory setting.[16,39] This may account for the translated clinical benefit of DB PCL reconstruction versus SB PCL reconstruction observed in our study that was previously absent when examining DB/SB ACL reconstruction.[10] Additionally, there have been concerns with the in vivo application of in vitro models. For example, a 2016 investigation by Hulsart-Billström et al[20] demonstrated a poor correlation between in vitro and in vivo testing of biomaterials for bone regeneration. Furthermore, in vitro models test for laxity at a time point immediately after the reconstructive procedure, while in vivo models examine laxity at a subsequent postoperative time point, making it challenging to predict the in vivo benefit of an in vitro observation. Despite these concerns, in the present meta-analysis, the improved pooled in vitro stability demonstrated by the DB group did translate to improved pooled in vivo stability, as patients treated with DB PCL reconstruction had decreased laxity on stress radiographs as compared with patients treated with SB PCL reconstruction.

Previous clinical investigations have attempted to examine whether the biomechanical benefit of DB reconstruction observed in a controlled laboratory setting translates to clinical practice. Several studies have reported that anatomic DB PCL reconstruction led to improved IKDC scores, reduced posterior tibial translation, and enhanced restoration of native knee kinematic function relative to the SB technique.[5,27] Furthermore, randomized controlled trials by Yoon et al[53] and Li et al[30] demonstrated superior clinical outcomes associated with DB reconstruction versus SB reconstruction. The present meta-analysis reflected the findings of these previous clinical investigations and revealed a statistically significant benefit in the majority of clinical outcomes. However, it is important to note that the WMD observed in the subjective IKDC score was just 3.64 points, which is of unclear clinical significance. Additionally, there have been concerns with the implementation of the technically challenging DB PCL reconstruction procedure because it introduces the risk of femoral fracture through tunnel collapse when reaming the second tunnel.[6,7] While valid, this concern can be offset with slight divergence of the femoral tunnels.[6,7] The present meta-analysis found that DB PCL reconstruction had no difference in risk of a major complication relative to the SB technique, suggesting that it is a safe and efficacious procedure. Thus, in the context of the previous clinical literature, the results of this meta-analysis reflect a significant clinical benefit to DB PCL reconstruction and suggest that the biomechanical benefit observed when reconstructing native anatomy in cadaveric specimens translated to improved clinical patient outcomes and with a similar safety profile.

Three previous meta-analyses aimed to summarize the literature comparing the DB and SB PCL reconstruction techniques.[5,26,29] In a 2017 meta-analysis, Lee et al[29] pooled 10 cadaveric biomechanical studies and demonstrated a significant biomechanical benefit of DB PCL reconstruction when resisting posterior tibial translation but no difference between the groups for external rotational laxity and varus laxity. It is important to note that the authors were able to pool only 2 to 4 biomechanical studies when assessing external rotation/varus laxity, and this may have contributed to nonsignificant results with external rotation at higher knee flexion angles. Like the study by Lee et al,[29] the biomechanical results of the present meta-analysis reflect superior resistance to posterior tibial translation in the DB PCL reconstruction group. Novel to our study, DB PCL reconstruction also demonstrated superior resistance to external rotation at 90° of knee flexion when pooling the biomechanical results of 7 controlled laboratory investigations.

In a 2022 meta-analysis of 13 comparative clinical investigations, Krott et al[26] reported no benefit to DB PCL reconstruction beyond objective translational laxity. It is interesting that the authors concluded that there was no difference between the reconstruction techniques, despite their results showing an objective clinical benefit with decreased tibial translation measured on Telos stress radiographs for DB PCL. Like the findings by Krott et al, our results did not initially reveal a significant difference in objective IKDC scores between the groups. However, upon subgroup analysis of the randomized controlled trials, our results suggest that DB PCL reconstruction leads to significantly higher odds of achieving normal or nearly normal objective IKDC outcomes. These findings likely accounted for the different conclusions reached between their study and ours. Additionally, similar to the previous meta-analysis, the present study revealed a significant objective benefit to DB PCL reconstruction during stress radiographs. Finally, unlike the study by Krott et al, the present meta-analysis found a statistically significant clinical benefit in the form of superior subjective IKDC outcomes.

Our presented meta-analysis is not without limitations. First, as a meta-analysis, it is inherently limited by the study design of the publications as well as inevitable variations in surgical techniques among the authors. Additionally, like any systematic review or meta-analysis, it is possible that a relevant article or patient population was not identified with our search criteria/screen. Furthermore, several outcomes were not explicitly reported by the authors and thus were extracted from a subsequent meta-analysis that included that investigation or were approximated from figures in the study. There is also a paucity of high-quality clinical literature examining these PCL reconstruction techniques, as 8 of the 13 clinical studies are level 3 evidence and 5 are level 2 evidence, which intrinsically limit the applicability of these findings.

Another major limitation of this investigation is that the clinical studies did not report outcomes as number of patients reaching the minimal clinically important difference, which made it challenging to assess the true clinical value of the statistically significant observations in this meta-analysis. In addition, it is unclear what degree of instability or posterior tibial translation is clinically relevant with regard to patient symptoms and risk of future degenerative changes. The ex vivo biomechanical findings of this meta-analysis also have limited applicability to in vivo applications and do not factor tissue healing or other biologic processes during evaluation. Furthermore, the biomechanical studies largely used cadaveric specimens from elderly donors. Thus, the findings in these investigations may not be representative of the younger, more active patient populations that typically undergo PCL reconstruction.

Last, the investigations may have had concomitant pathology and procedures, which may have influenced outcomes in this meta-analysis. Future randomized investigations are necessary to evaluate the true biomechanical and clinical benefit of DB PCL reconstruction relative to SB PCL reconstruction.

CONCLUSION

DB PCL reconstruction leads to superior biomechanical outcomes and clinical outcomes relative to SB PCL reconstruction. Re-creating native anatomy during PCL reconstruction maximizes biomechanical stability and clinical outcomes.

ORCID iD

Suhas P. Dasari https://orcid.org/0000-0001-7161-7305

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REFERENCES

1. Apsingi S, Nguyen T, Bull AMJ, et al. Control of laxity in knees with combined posterior cruciate ligament and posterolateral corner deficiency. *Am J Sports Med*. 2008;36(3):487-494.
2. Apsingi S, Nguyen T, Bull AMJ, et al. The role of PCL reconstruction in knees with combined PCL and posterolateral corner deficiency. *Knee Surg Sports Traumatol Arthrosc*. 2008;16(2):104-111.
3. Bergfeld JA, Graham SM, Parker RD, Valdevit AD, Kambic HE. A biomechanical comparison of posterior cruciate ligament reconstructions using single- and double-bundle tibial inlay techniques. *Am J Sports Med*. 2005;33(7):976-981.
4. Borenstein M, Hedges LV, Higgins JP, Rothstein HR. A basic introduction to fixed-effect and random-effects models for meta-analysis. *Res Synth Methods*. 2010;1(2):97-111.
5. Chahla J, Moatshe G, Cinque ME, et al. Single-bundle and double-bundle posterior cruciate ligament reconstructions: a systematic review and meta-analysis of 441 patients at a minimum 2 years' follow-up. *Arthroscopy*. 2017;33(11):2066-2080.
6. Chahla J, Moatshe G, Engebretsen L, LaPrade RF. Anatomic double-bundle posterior cruciate ligament reconstruction. *JBJS Essent Surg Tech*. 2017;7(1):e4.
7. Chahla J, Nitri M, Civitarese D, et al. Anatomic double-bundle posterior cruciate ligament reconstruction. *Arthrosc Tech*. 2016;5(1):e149-e156.

8. Chahla J, von Bormann R, Engebretsen L, LaPrade RF. Anatomic posterior cruciate ligament reconstruction: state of the art. *J ISAKOS*. 2016;1(5):292-302.
9. Chahla J, Williams BT, LaPrade RF. Posterior cruciate ligament. *Arthroscopy*. 2020;36(2):333-335.
10. Chen H, Chen B, Tie K, Fu Z, Chen L. Single-bundle versus double-bundle autologous anterior cruciate ligament reconstruction: a meta-analysis of randomized controlled trials at 5-year minimum follow-up. *J Orthop Surg Res*. 2018;13(1):50.
11. Deie M, Adachi N, Nakamae A, Takazawa K, Ochi M. Evaluation of single-bundle versus double-bundle PCL reconstructions with more than 10-year follow-up. *ScientificWorldJournal*. 2015;2015:751465.
12. Fanelli GC, Beck JD, Edson CJ. Single compared to double-bundle PCL reconstruction using allograft tissue. *J Knee Surg*. 2012;25(1):59-64.
13. Gollehon DL, Torzilli PA, Warren RF. The role of the posterolateral and cruciate ligaments in the stability of the human knee. A biomechanical study. *J Bone Joint Surg Am*. 1987;69(2):233-242.
14. Grood ES, Stowers SF, Noyes FR. Limits of movement in the human knee. Effect of sectioning the posterior cruciate ligament and posterolateral structures. *J Bone Joint Surg Am*. 1988;70(1):88-97.
15. Guo NA, Qi Y, Yang B, et al. The biomechanical study of different posterior cruciate ligament reconstruction techniques. *J Mech Med Biol*. 2018;18(8):1840025.
16. Harner CD, Janaushek MA, Kanamori A, et al. Biomechanical analysis of a double-bundle posterior cruciate ligament reconstruction. *Am J Sports Med*. 2000;28(2):144-151.
17. Hatayama K, Higuchi H, Kimura M, et al. A comparison of arthroscopic single- and double-bundle posterior cruciate ligament reconstruction: review of 20 cases. *Am J Orthop (Belle Mead NJ)*. 2006;35(12):568-571.
18. Houe T, Jørgensen U. Arthroscopic posterior cruciate ligament reconstruction: one- vs two-tunnel technique. *Scand J Med Sci Sports*. 2004;14(2):107-111.
19. Hozo SP, Djulbegovic B, Hozo I. Estimating the mean and variance from the median, range, and the size of a sample. *BMC Med Res Methodol*. 2005;5(1):13.
20. Hulsart-Billström G, Dawson JI, Hofmann S, et al. A surprisingly poor correlation between in vitro and in vivo testing of biomaterials for bone regeneration: results of a multicentre analysis. *Eur Cell Mater*. 2016;31:312-322.
21. Jain V, Goyal A, Mohindra M, et al. A comparative analysis of arthroscopic double-bundle versus single-bundle posterior cruciate ligament reconstruction using hamstring tendon autograft. *Arch Orthop Trauma Surg*. 2016;136(11):1555-1561.
22. Kennedy NI, LaPrade RF, Goldsmith MT, et al. Posterior cruciate ligament graft fixation angles, part 2: biomechanical evaluation for anatomic double-bundle reconstruction. *Am J Sports Med*. 2014;42(10):2346-2355.
23. Kennedy NI, Wijdicks CA, Goldsmith MT, et al. Kinematic analysis of the posterior cruciate ligament, part 1. *Am J Sports Med*. 2013;41(12):2828-2838.
24. Kim SJ, Jung M, Moon HK, Kim SG, Chun YM. Anterolateral transtibial posterior cruciate ligament reconstruction combined with anatomical reconstruction of posterolateral corner insufficiency: comparison of single-bundle versus double-bundle posterior cruciate ligament reconstruction over a 2- to 6-year follow-up. *Am J Sports Med*. 2011;39(3):481-489.
25. Kim SJ, Kim TE, Jo SB, Kung YP. Comparison of the clinical results of three posterior cruciate ligament reconstruction techniques. *J Bone Joint Surg Am*. 2009;91(11):2543-2549.
26. Krott NL, Wengle L, Whelan D, Wild M, Betsch M. Single and double bundle posterior cruciate ligament reconstruction yield comparable clinical and functional outcomes: a systematic review and meta-analysis. *Knee Surg Sports Traumatol Arthrosc*. 2022;30(7):2388-2399.
27. LaPrade RF, Floyd ER, Falaas KL, et al. The posterior cruciate ligament: anatomy, biomechanics, and double-bundle reconstruction. *J Arthrosc Surg Sports Med*. 2021;2:94-107.
28. Lee D-Y, Park Y-J, Kim D-H, et al. The role of isolated posterior cruciate ligament reconstruction in knees with combined posterior cruciate ligament and posterolateral complex injury. *Knee Surg Sports Traumatol Arthrosc*. 2018;26(9):2669-2678.
29. Lee DY, Kim DH, Kim HJ, et al. Biomechanical comparison of single-bundle and double-bundle posterior cruciate ligament reconstruction: a systematic review and meta-analysis. *JBJS Rev*. 2017;5(10):e6.
30. Li Y, Li J, Wang J, Gao S, Zhang Y. Comparison of single-bundle and double-bundle isolated posterior cruciate ligament reconstruction with allograft: a prospective, randomized study. *Arthroscopy*. 2014;30(6):695-700.
31. Lipscomb AB, Anderson AF, Norwig ED, Hovis WD, Brown DL. Isolated posterior cruciate ligament reconstruction. *Am J Sports Med*. 1993;21(4):490-496.
32. Logterman SL, Wydra FB, Frank RM. Posterior cruciate ligament: anatomy and biomechanics. *Curr Rev Musculoskel Med*. 2018;11(3):510-514.
33. Mannor DA, Shearn JT, Grood ES, Noyes FR, Levy MS. Two-bundle posterior cruciate ligament reconstruction: an in vitro analysis of graft placement and tension. *Am J Sports Med*. 2000;28(6):833-845.
34. Markolf KL, Feeley BT, Jackson SR, McAllister DR. Biomechanical studies of double-bundle posterior cruciate ligament reconstructions. *J Bone Joint Surg Am*. 2006;88(8):1788-1794.
35. Markolf KL, Jackson SR, McAllister DR. Single- versus double-bundle posterior cruciate ligament reconstruction: effects of femoral tunnel separation. *Am J Sports Med*. 2010;38(6):1141-1146.
36. McAllister DR, Petrigliano FA. Diagnosis and treatment of posterior cruciate ligament injuries. *Curr Sports Med Rep*. 2007;6(5):293-299.
37. Milles JL, Nuelle CW, Pfeiffer F, et al. Biomechanical comparison: single-bundle versus double-bundle posterior cruciate ligament reconstruction techniques. *J Knee Surg*. 2017;30(4):347-351.
38. Nuelle CW, Milles JL, Pfeiffer FM, et al. Biomechanical comparison of five posterior cruciate ligament reconstruction techniques. *J Knee Surg*. 2017;30(6):523-531.
39. Oh J-Y, Kim K-T, Park Y-J, et al. Biomechanical comparison of single-bundle versus double-bundle anterior cruciate ligament reconstruction: a meta-analysis. *Knee Surg Relat Res*. 2020;32(1):14.
40. Pache S, Aman ZS, Kennedy M, et al. Posterior cruciate ligament: current concepts review. *Arch Bone Jt Surg*. 2018;6(1):8-18.
41. Page MJ, McKenzie JE, Bossuyt PM, et al. The PRISMA 2020 statement: an updated guideline for reporting systematic reviews. *BMJ*. 2021;372:N71.
42. Race A, Amis AA. PCL reconstruction: in vitro biomechanical comparison of ''isometric'' versus single and double-bundled ''anatomic'' grafts. *J Bone Joint Surg Br*. 1998;80(1):173-179.
43. Shelbourne KD, Clark M, Gray T. Minimum 10-year follow-up of patients after an acute, isolated posterior cruciate ligament injury treated nonoperatively. *Am J Sports Med*. 2013;41(7):1526-1533.
44. Shon OJ, Lee DC, Park CH, Kim WH, Jung KA. A comparison of arthroscopically assisted single and double bundle tibial inlay reconstruction for isolated posterior cruciate ligament injury. *Clin Orthop Surg*. 2010;2(2):76-84.
45. Slim K, Nini E, Forestier D, et al. Methodological Index for Non-randomized Studies (MINORS): development and validation of a new instrument. *ANZ J Surg*. 2003;73(9):712-716.
46. Sterne JAC, Savović J, Page MJ, et al. RoB 2: a revised tool for assessing risk of bias in randomised trials. *BMJ*. 2019:L4898.
47. Wang CJ, Weng LH, Hsu CC, Chan YS. Arthroscopic single- versus double-bundle posterior cruciate ligament reconstructions using hamstring autograft. *Injury*. 2004;35(12):1293-1299.
48. Whiddon DR, Zehms CT, Miller MD, et al. Double compared with single-bundle open inlay posterior cruciate ligament reconstruction in a cadaver model. *J Bone Joint Surg Am*. 2008;90(9):1820-1829.
49. Wijdicks CA, Kennedy NI, Goldsmith MT, et al. Kinematic analysis of the posterior cruciate ligament, part 2: a comparison of anatomic single- versus double-bundle reconstruction. *Am J Sports Med*. 2013;41(12):2839-2848.

50. Wiley WB, Askew MJ, Melby A 3rd, Noe DA. Kinematics of the posterior cruciate ligament/posterolateral corner-injured knee after reconstruction by single- and double-bundle intra-articular grafts. *Am J Sports Med*. 2006;34(5):741-748.
51. Wilke J, Krause F, Niederer D, et al. Appraising the methodological quality of cadaveric studies: validation of the QUACS scale. *J Anat*. 2015;226(5):440-446.
52. Xu M, Zhang Q, Dai S, et al. Double bundle versus single bundle reconstruction in the treatment of posterior cruciate ligament injury: a prospective comparative study. *Indian J Orthop*. 2019;53(2):297-303.
53. Yoon KH, Bae DK, Song SJ, Cho HJ, Lee JH. A prospective randomized study comparing arthroscopic single-bundle and double-bundle posterior cruciate ligament reconstructions preserving remnant fibers. *Am J Sports Med*. 2011;39(3):474-480.
54. Yoon KH, Kim EJ, Kwon YB, Kim S-G. Minimum 10-year results of single- versus double-bundle posterior cruciate ligament reconstruction: clinical, radiologic, and survivorship outcomes. *Am J Sports Med*. 2019;47(4):822-827.
55. Zhao J-X, Zhang L-H, Mao Z, et al. Outcome of posterior cruciate ligament reconstruction using the single- versus double bundle technique: a meta-analysis. *J Int Med Res*. 2015;43(2):149-160.