The incidence of tibial tunnel coalition is higher than femoral tunnel coalition in double-bundle anterior cruciate ligament reconstruction using hamstring autografts: A…

Nakanishi, Yuta ; Nagai, Kanto ; Kay, Jeffrey ; Zakharia, Alexander ; Nukuto, Koji ; Hoshino, Yuichi ; Matsushita, Takehiko ; Kuroda, Ryosuk…

(Citation)
Orthopaedics & Traumatology: Surgery & Research,108(8):103407

(Issue Date)
2022-12

(Resource Type)
journal article

(Version)
Accepted Manuscript

The Incidence of Tibial Tunnel Coalition is Higher Than Femoral Tunnel Coalition in Double-Bundle Anterior Cruciate Ligament Reconstruction Using Hamstring Autografts: A Systematic Review

Yuta Nakanishi, MD[1], Kanto Nagai, MD, PhD[1], Jeffrey Kay MD[2], Alexander Zakharia[3], Koji Nukuto, MD[1], Yuichi Hoshino, MD, PhD [1], Takehiko Matsushita, MD, PhD [1], Ryosuke Kuroda MD, PhD [1], Darren de SA, MBA(c), MD, FRCSC [2]

1. Department of Orthopaedic Surgery, Kobe University Graduate School of Medicine, Kobe, Hyogo, Japan
2. Division of Orthopaedic Surgery, Department of Surgery, McMaster University Medical Centre, Hamilton, ON, Canada
3. MacSports Research Program, McMaster University, Hamilton, ON, Canada

Corresponding author

- Name: Kanto Nagai, MD, PhD
- Institutional address:

  Department of Orthopaedic Surgery, Kobe University Graduate School of Medicine,

  7-5-1, Kusunoki-cho, Chuo-ku, Kobe, Hyogo, 650-0017, Japan
- Phone: +81-78-382-5985
- Email: nagaik@med.kobe-u.ac.jp

Abstract

Introduction: Intra-operative and post-operative coalition of tunnels may occur in double-bundle (DB) anterior cruciate ligament reconstruction (ACLR). However, the incidence and effect on clinical outcomes of tunnel coalition following primary DB ACLR using a hamstring autograft has yet be analyzed, and thus remains unknown. The objective of this systematic review was to identify the incidence of tunnel coalition upon DB ACLR using hamstring autografts and to elucidate any clinical outcomes and/or complications that tunnel coalition may have post-operatively.

Hypothesis: The incidence of tunnel coalition would increase in respect to time from the index surgery, and that tunnel coalition would be related to poorer clinical outcomes compared to non-coalition cases.

Methods: Three databases (PubMed, EMBASE, Cochrane Library) were searched in accordance with PRISMA and R-AMSTAR guidelines on June 15, 2020. Relevant studies were screened in duplicate and data regarding patient demographics, incidence of femoral and tibial tunnel coalition, and outcomes were extracted. Coalition rate was also compared between follow up at 1 month or less defined as "shorter-term", and 6 months or greater as "longer-term". Coalition is defined as the missing of a bony bridge between the two tunnels.

Results: 36 studies examining 1,574 patients, mean age 29.1 years, were included in this study. 29 studies (1,110 knees) reported the incidence of femoral coalition with a pooled rate of coalition of 8% (95% CI=4%-12%). 28 studies (1,129 knees) reported an incidence of tibial coalition with a pooled rate of coalition of 21% (95% CI=13%-30%). The incidence of tibial coalition was significantly higher than the incidence of femoral coalition across 21 comparative studies (OR=3.37, 95% CI=1.41-8.09, p=0.0065). Only two studies (111 knees) compared tunnel coalition and non-coalition groups for clinical outcome and no significant differences were observed with regards to Lysholm score, Tegner activity scale, and knee laxity measured with a KT-1000 arthrometer.

Discussion: The rate of tibial tunnel coalition in DB ACLR is higher than femoral tunnel coalition, particularly at longer-term follow-up. Despite the higher radiographic evidence of coalition, the clinical effects of such remain to be ascertained, and further comparative studies are required to facilitate this understanding.

Level of evidence: Level IV, systematic review of Level I-IV studies

Keywords: Anterior cruciate ligament; Anterior cruciate ligament reconstruction; Bone tunnel widening; Bone tunnel enlargement, Coalition, Double-bundle

1. INTRODUCTION

Anterior cruciate ligament reconstruction (ACLR) using hamstring autografts is a widely used versatile option that can be broadly divided into either a single-bundle (SB) or double-bundle (DB) technique [1,2]. Anatomic DB ACLR has been reported to improve clinical outcomes with fewer incidents of graft failure [3–7].

DB ACLR typically requires the creation of two femoral tunnels and two tibial tunnels for the anteromedial (AM) and posterolateral (PL) bundles [8]. By consensus, a reasonably sized bone bridge between each tunnel is estimated to be 2 to 3mm to avoid tunnel coalition [9]. Tunnel coalition may cause increased anterior tibial translation and rotatory laxity [8,10]. Post-operative coalition as a result of tunnel enlargement has also been observed [11,12], which could lead to the subsequent formation of a single enlarged tunnel. This may compromise the interference fit of a soft-tissue graft within a bone tunnel in the acute phase, and potentially complicate and/or pose technical challenges in the revision scenario, should it be required [13,14]. Despite careful creation of tunnels, reports on the incidence of tunnel coalition on the femoral side ranges from 2 to 10%, while the tibial side has been observed in up to 77% [15]. However, the incidence and effect on clinical outcomes of tunnel coalition following primary DB ACLR using a hamstring autograft has yet be critically analyzed. Therefore, the purpose of this original systematic review was to identify the incidence of tunnel coalition upon DB ACLR using hamstring autografts and to elucidate any clinical outcomes and/or complications that tunnel coalition may have post-operatively. We hypothesized that the incidence of tunnel coalition would increase in respect to time from the index surgery, and that tunnel coalition would be related to poorer clinical outcomes compared to non-coalition cases.

2. MATERIALS AND METHODS

2.1 Search strategy

Two reviewers searched three databases (PubMed, EMBASE, Cochrane Library) in accordance with the preferred reporting items for systematic review and meta-analyses (PRISMA) and Revised-A Measurement Tool to Assess Systematic Reviews (R-AMSTAR) guidelines on June 15, 2020 [16,17]. Inclusion criteria were as follows: all levels of evidence; primary DB ACLR; use of hamstring autografts; reports incidence of coalition. Studies were excluded if: basic science studies; animal studies; cadaveric studies; non-English studies; synthetic graft use; no full-text publications available. Skeletal maturity and minimum follow-up period were not included in the criteria.

The search was conducted using the terms double-bundle AND anterior cruciate ligament reconstruction AND (enlargement OR coalition OR communication OR widening OR bridge OR tunnel). Details of the screening process are outlined in Fig. 1.

2.2 Study screening

Two independent reviewers screened titles, abstracts, and full-texts of the retrieved citations. A third senior reviewer was consulted to mediate any unresolved disputes in screening. The references of all included studies were further screened to include articles that may have eluded the initial search.

2.3 Quality assessment

Quality assessment of randomized controlled trial (RCT) studies was performed using the Detsky Quality Assessment Scale [18]. Whereas, Quality assessment of non-randomized cohort studies and case series was performed using the Methodological Index for Non-Randomized Studies (MINORS) quality assessment tool [19].

2.4 Data abstraction

Data were abstracted in duplicate by two reviewers and recorded in a Google Sheets spreadsheet. The abstracted data included the authors, study design and corresponding level of evidence, recruitment period, sources of funding, number of operated knees before and after loss to follow-up, follow-up duration, patient demographics (i.e. sample size, age, sex), tunnel creation technique, location of coalition, and all reported pre- and post-operative clinical and functional outcomes. Kappa (κ) value was calculated for each stage of article screening to assess inter-reviewer agreement during title, abstract, and full-text screening. Descriptive statistics, such as means, ranges, and measure of variance (e.g. standard deviations, 95% confidence intervals (CI)) are presented when applicable. Intraclass correlation coefficient (ICC) was used to assess inter-reviewer agreement for Detsky and MINORS quality assessment scores. In reference to a previous study, the categorization of ICC scores was determined *a priori* as follows: ICC < 0.50 indicates poor agreement, $0.50 \leq$ ICC < 0.75 indicates moderate agreement, $0.75 \leq$ ICC < 0.90 indicates good agreement, and ICC ≥ 0.90 indicates excellent agreement [20]. An *a priori* categorization of the Detsky scores was set as follows: ≤75% unsatisfactory level of methodological quality, >75% satisfactory level of methodological quality [21]. An *a priori* categorization of the MINORS score was set as follows: $0 <$ MINORS score < 6 to indicate very low quality of evidence, $6 \leq$ MINORS score < 10 to indicate low quality of evidence, $10 \leq$ MINORS score < 14 to indicate fair quality of evidence, and MINORS score $\geq$ 14 to indicate good quality of evidence for non-randomized studies [22].

2.5 Statistical Analysis

The primary outcome was the incidence of coalition across studies, and the secondary outcome were any post-operative functional outcomes reported across the included studies. A meta-analysis of proportions was conducted to determine the pooled incidence of coalition across studies. Subgroup analyses were conducted where possible. In order to establish the variance of the raw proportions, a Freeman-Tukey transformation was applied [23]. The transformed proportions were then combined using the DerSimonian-Laird random effects model (to incorporate the anticipated heterogeneity) [24]. The proportions were back-transformed using an equation derived by Miller [25]. Where applicable, proportions of dichotomous outcomes were compared using odds ratios and a random effects mode given the anticipated heterogeneity across studies. The I^2 test was used to assess heterogeneity. Values of I^2 between 25% and 49% were considered low, 50% and 74% moderate, and values greater than 75% considered to be high statistical heterogeneity [26]. For other variables, where results were presented in a non-uniform nature across studies, the results are presented in narrative summary fashion. Descriptive statistics were calculated including means, standard deviations, counts, proportions, and ranges. Calculations were conducted using StatsDirect statistical software (Version 3.2.7, StatsDirect software, Cheshire, UK).

3. RESULTS

3.1 Study Quality

The initial search strategy yielded 543 unique studies, of which 36 met the inclusion and exclusion criteria for this review [11,12,15,27–59]. No additional studies were included after manually searching the references of the included studies (Fig. 1).

Among the 36 studies included in this systematic review, three were level I evidence, seven were level II evidence, 11 were level III evidence, and 15 were level IV evidence. Six of the included studies were RCTs (17%). The reviewers reached good agreement in Detsky scores with an ICC of 0.784 (95% CI=0.765-0.803). The mean Detsky score among the RCTs was 88.33% ± 5.56%. All six RCTs had a satisfactory methodological quality (Table 1). The remaining 30 studies included were non-randomized (16 case series, 44%; eight retrospective cohort studies, 22%; six prospective cohort studies, 17%). The reviewers reached good agreement in MINORS scores with an ICC of 0.76 (95% CI=0.33-0.93). The mean MINORS score among the non-randomized studies was 78.49% ± 10.76%. One non-randomized study had low quality of evidence, 11 had fair quality of evidence, and 18 had good quality of evidence (Table 1).

3.2 Study Characteristics

All included studies were published between 2007 and 2019. A total of 1,574 patients were included at the final reported follow-up across the studies, with 1,098 males (69.8%) and 476 females (30.2%). The pooled mean age of the patients included was 29.1 years (range, 12 to 63 years), and the mean follow-up duration was 27.4 months (range, 7 to 60 months). Study characteristics are presented in Table 1.

3.3 Incidence of Coalition

Twenty-one studies (714 knees) assessed the incidence of both femoral and tibial coalition. The incidence of femoral coalition was greater than the incidence of tibial coalition in three of these studies (68 knees), whereas the incidence of tibial coalition was greater than the incidence of femoral coalition in 14 of these studies (502 knees). The incidence of tibial coalition was significantly higher than the incidence of femoral coalition across these studies (odds ratio=3.37 95% CI=1.41-8.09, p=0.0065).

Specifically, the incidence of femoral and tibial coalition were reported in 29 studies (1,110 knees) and 28 studies (1,129 knees), respectively. The rates of femoral and tibial coalition ranged from 0 to 64% and from 0 to 77%, with a pooled rate of coalition of 8% (95% CI=4% to 12%, I^2=82%) (Fig. 2) and 21% (95% CI=13% to 30%, I^2=91.8%) (Fig. 3), respectively. The incidence of femoral tunnel coalition was measured exclusively by MRI or CT in 10 studies (344 knees) and 15 studies (561 knees), respectively. The incidence of femoral coalition measured on MRI ranged from 0 to 48% with a pooled rate of coalition of 6.7% (95% CI=1.3% to 15%). The incidence of femoral coalition measured on CT ranged from 0 to 64% with a pooled rate of coalition of 11% (95% CI=4.9% to 20%). On the other hand, the incidence of tibial tunnel coalition was measured exclusively by MRI or CT in 10 studies (344 knees) and 13 studies (614 knees), respectively. The incidence of tibial coalition measured on MRI ranged from 0 to 43% with a pooled rate of coalition of 18% (95% CI=9.4% to 2.9%). The incidence of tibial coalition measured on CT ranged from 0 to 77% with a pooled rate of coalition of 30% (95% CI=16% to 45%).

Seven studies (228 knees) reported femoral coalition at both shorter-term (<1 months) and longer-term (>6 months) follow-up. This categorization was informed by the data reported in the studies included. Femoral coalition at shorter-term follow-up ranged from 0 to 5% with a pooled coalition of 1% (95% CI=0% to 2.7%), and at longer-term follow-up ranged from 0% to 19% with a pooled coalition of 3.7% (95% CI=1% to 8.5%). The difference between coalition at shorter-term and longer-term follow-up was not significant (odds ratio=3.2, 95% CI=0.98-10.3, N.S.). On the other hand, six studies (208 knees) reported tibial coalition at both shorter-term (<1 months) and longer-term (>6 months) follow-up. Tibial coalition at shorter-term follow-up ranged from 0 to 63% with a pooled coalition of 24% (95% CI=5% to 50%), and at longer-term follow-up ranged from 0 to 77% with a pooled coalition of 37% (95% CI=11% to 68%). There was a significantly higher rate of tibial coalition at longer-term follow-up compared to shorter-term follow-up (odds ratio=2.17, 95% CI=1.3-3.56, p=0.0021).

3.4 Functional Outcomes

There was a paucity of studies reporting post-operative clinical outcomes. Only two studies (111 knees) compared clinical results between groups with and without tunnel coalition [11,43]. There was no significant difference in Lysholm score, Tegner activity scale, or knee laxity between these groups in either study. However, one study (52 patients) noted significantly greater knee flexion ranges among patients with tibial tunnel coalition (tibial tunnel coalition: 153.8°, tibial tunnel non-coalition: 145.9°, p = 0.006) [11].

Nine studies (436 knees) reported pre-operative Lysholm scores with mean scores ranging from 52.4 to 72.7. Post-operative Lysholm scores among these nine studies (436 knees) ranged from 84.6 to 94.8.

Six studies (256 knees) reported pre-operative Tegner scores with mean scores ranging from 1.5 to 7.0. Post-operative Tegner scores were reported in seven studies (334 knees), with mean scores ranging from 5.2 to 7.1.

Fourteen studies (594 knees) reported pre-operative knee laxity, with mean measurements ranging from >3 to 7.0mm. Post-operative knee laxity was reported in twenty-one studies (905 knees), with mean measurements ranging from 0.1 to 2.1mm.

4. DISCUSSION

The main finding of the present study was that the rate of tibial tunnel coalition was higher than femoral tunnel coalition, particularly at longer-term (>6 months) follow-up. Rates of both tibial and femoral tunnel coalition are highest on CT, followed by MRI. Another key finding was that there is currently a lack of data available to deduce the true effect of tunnel coalition on functional outcomes.

One proposed mechanism for the high rates of tibial tunnel coalition compared to femoral tunnel coalition across the studies included within this review is that the oval shape of the AM tibial tunnel and its close proximity to the PL tibial tunnel permits frequent overlap at the proximal aspect between the tunnels, as previously reported [15]. This subsequently allows greater inflow of synovial fluid into the overlapping tunnels, promoting transverse movement at the proximal point of tunnel coalition throughout the range of motion [15,60]. Moreover, the size of the graft tends to be larger on the tibial side compared to the femoral side, since the sutures that secure the strands together are usually performed on the tibial side, thereby increasing the diameter of the graft [12]. It has also been suggested that great variance exists between native ACL insertion size and the cross-sectional area of the grafts, in which case, the graft may be oversized compared to the native ACL footprint [61]. For these reasons, mismatch of graft size and tibial footprint may occur, potentially causing intra-operative coalition of the tibial AM and PL bone tunnels, although the use of intraoperative fluoroscopy has been suggested to assist in the placement of anatomically-accurate tunnel location.[12,51,62]. Other reasons for tibial or femoral tunnel coalition include tunnel enlargement due to micromotion of the graft, fixation methods, accelerated rehabilitation, and tunnel placement [27,43,51,60,63–66].

Various modalities were used to measure the incidence of tunnel coalition in the literature which may have caused inconsistencies in the reported rates of tunnel coalition among different studies. The current review shows rates of both tibial and femoral tunnel coalition to be highest on CT, followed by MRI (Table 2). Although CT scans have been suggested to be the most reliable method when analyzing bone tunnels, a recent prospective study revealed no significant differences between CT and MRI when examining tunnel positioning following ACLR[67–69]. Although CT risks exposing patients to a greater radiation dose than other modalities, use of appropriate protection can ameliorate the associated risks [70]. Moreover, recent clinical findings have developed new protocols demonstrating low radiation exposure [68,71]. Therefore, the information obtained from high-definition CT scans utilizing appropriate protection and lower radiation doses may outweigh the risks associated with CT-mediated radiation exposure. Computer simulation models have recently been developed which permit limitless reorientation and movement of models. Although not yet widely available, it may prove to be useful in evaluating bone tunnel coalition after ACLR [72].

Differences in the anatomic location chosen to evaluate incidence of tunnel coalition may have also caused discrepancy in the reported rates of tunnel coalition. The most common locations of measurement were the intra-articular aperture (18 studies, 50.0%) and 10mm from the intra-articular aperture (five studies, 13.9%). There were four studies (11.1%) that measured tunnel coalition at both the intra-articular aperture and 10mm from the intra-articular aperture. These three reference points account for 75.0% of the locations used for tunnel coalition evaluation. Consistent protocol for measurement is preferable for comparison between future studies. Evaluation at the aperture is a logical choice and has been shown to have the greatest incidence of coalition within the tunnel [43,48]. However, evaluation at 10mm from the aperture may also be sufficient since the majority of the coalition occurs <10mm [43].

Tunnel coalition as a consequence of post-operative tunnel enlargement may occur, and tunnel osteolysis is a suspected factor for tunnel enlargement. Pressure effect by graft swelling may cause local necrosis of the tunnels, thereby increasing exposure of the graft tunnel interface from the intra-articular aperture to the distal end of the tunnel, allowing ingress of synovial fluid containing osteolytic cytokines [27,73]. The use of narrower tunnels in DB ACLR facilitates less synovial fluid ingression, mitigating exposure to synovial fluid-resident osteolytic cytokines, and thus yields less osteolytic tunnel enlargement relative to SB ACLR [51]. Nevertheless, micromotion of the graft remains to be the predominant factor in provoking tunnel enlargement [51].

The secondary outcome of this study was to assess whether tunnel coalition influences post-operative clinical and functional outcomes following DB ACLR. Only two studies (111 patients) compared these outcomes between tunnel coalition and non-coalition groups. The clinical follow-up was performed at 1 year and 2 years (mean 25.4 months, range, 24 to 33 months) [11,43]. The results showed no significant difference with respect to clinical and functional outcomes such as Lysholm score, Tegner score, post-operative objective IKDC score, anterior laxity and rotational laxity [11,43]. However, the sample size was small and follow-up period was short, and therefore, the result may be a type II error. Although a previous randomized controlled trial (66 patients) found that the range of motion in flexion was slightly greater following tibial tunnel coalition than non-coalesced tunnels, its clinical significance was suggested to be minimal, and no statistical significance was seen between other clinical evaluations, such as knee laxity, IKDC function score, and Lysholm score [11]. Future studies with a larger population size and longer follow-up directly comparing coalition and non-coalition groups in DB ACLR are needed to elucidate any effect that coalition may have on clinical outcome.

Limitations in this review were that many of the studies included were levels III (27.8%) and IV (44.4%), and thus there is inherent bias from the retrospective nature of these methodological designs. There was also potential overlap of patients from different papers that were written by the same author and institution, potentially introducing selection bias. However, to be inclusive, all relevant papers were included unless complete overlap of the patient group was clearly identified.

5. CONCLUSION

The rate of tibial tunnel coalition in DB ACLR is higher than femoral tunnel coalition, particularly at longer-term follow-up. Despite the higher radiographic evidence of coalition, the clinical effects of such remain to be ascertained, and further comparative studies are required to facilitate this understanding.

Disclosure of interest

The authors declare no conflict of interest.

Funding

There was no funding for this study.

Authors' contributions

The co-authors and I warrant that all authors have participated in this study. Detailed contributions are as follows; Kanto Nagai (K.Na.), Yuichi Hoshino (Y.H.), Takehiko Matsushita (T.M.), Ryosuke Kuroda (R.K.), and Darren de SA (D.d.S.) conceived the study, and K.Na., Y.H., Yuta Nakanishi (Y.N.), Alexander Zakharia (A.Z.), and Koji Nukuto (K.Nu.) participated in the design of the study. Y.N. and K.Nu. performed the search, screening process, and assessment of study quality. Jeffrey Kay (J.K.) conducted the pertinent statistical tests and analyses. All authors participated in the interpretation of the data. Y.N., A.Z., K.Na., J.K. and D.d.S. wrote the manuscript, and all authors performed critical revision of the manuscript for intellectual content. All authors have read and approved the final manuscript.

Acknowledgements

None

6. REFERENCES

[1] Järvelä S, Kiekara T, Suomalainen P, Järvelä T. Double-bundle versus single-bundle anterior cruciate ligament reconstruction: a prospective randomized study with 10-year results. Am J Sports Med 2017;45:2578–85.

[2] Thaunat M, Fayard JM, Sonnery-Cottet B. Hamstring tendons or bone-patellar tendon-bone graft for anterior cruciate ligament reconstruction? Orthop Traumatol Surg Res 2019;105:S89-S94.

[3] Hoshino Y, Kuroda R, Nagamune K, Yagi M, Mizuno K, Yamaguchi M, et al. In vivo measurement of the pivot-shift test in the anterior cruciate ligament-deficient knee using an electromagnetic device. Am J Sports Med 2007;35:1098–104.

[4] Hussein M, van Eck CF, Cretnik A, Dinevski D, Fu FH. Prospective randomized clinical evaluation of conventional single-bundle, anatomic single-bundle, and anatomic double-bundle anterior cruciate ligament reconstruction. Am J Sports Med 2012;40:512–20.

[5] Morey VM, Nag HL, Chowdhury B, Sankineani SR, Naranje SM. A prospective comparative study of clinical and functional outcomes between anatomic double bundle and single bundle hamstring grafts for arthroscopic anterior cruciate ligament reconstruction. Int J Surg 2015;21:162–7.

[6] Siebold R, Dehler C, Ellert T. Prospective randomized comparison of double-bundle versus single-bundle anterior cruciate ligament reconstruction. Arthroscopy 2008;24:137–45.

[7] Svantesson E, Sundemo D, Senorski EH, Alentorn-Geli E, Musahl V, Fu FH, et al. Double-bundle anterior cruciate ligament reconstruction is superior to single-bundle reconstruction in terms of revision frequency: a study of 22,460 patients from the Swedish National Knee Ligament Register. Knee Surg Sports Traumatol Arthrosc 2017;25:3884–91.

[8] Araki D, Kuroda R, Kubo S, Fujita N, Tei K, Nishimoto K, et al. A prospective randomised study of anatomical single-bundle versus double-bundle anterior cruciate ligament reconstruction: quantitative evaluation using an electromagnetic measurement system. Int Orthop 2011;35:439–46.

[9] Lehmann AK, Osada N, Zantop T, Raschke MJ, Petersen W. Femoral bridge stability in double-bundle ACL reconstruction: impact of bridge width and different fixation techniques on the structural properties of the graft/femur complex. Arch Orthop Trauma Surg 2009;129:1127–32.

[10] Petersen W, Tretow H, Weimann A, Herbort M, Fu FH, Raschke M, et al. Biomechanical evaluation of two techniques for double-bundle anterior cruciate ligament reconstruction. Am J Sports Med 2007;35:228–34.

[11] Kiekara T, Järvelä T, Huhtala H, Paakkala A. MRI evaluation of the four tunnels of double-bundle ACL reconstruction. Acta Radiol 2014;55:579–88.

[12] Siebold R, Cafaltzis K. Differentiation between intraoperative and postoperative bone tunnel widening and communication in double-bundle anterior cruciate ligament reconstruction: a prospective study. Arthroscopy 2010;26(8):1066–73.

[13] Ohly NE, Murray IR, Keating JF. Revision anterior cruciate ligament reconstruction: timing of surgery and the incidence of meniscal tears and degenerative change. J Bone Joint Surg Br 2007;89:1051–4.

[14] Zantop T, Diermann N, Schumacher T, Schanz S, Fu FH, Petersen W. Anatomical and nonanatomical double-bundle anterior cruciate ligament reconstruction. Am J Sports Med 2008;36:678–85.

[15] Kawaguchi Y, Kondo E, Onodera J, Kitamura N, Sasaki T, Yagi T, et al. Tunnel enlargement and coalition after anatomic double-bundle anterior cruciate ligament reconstruction with hamstring tendon autografts: a computed tomography study. Orthop J Sports Med 2013;1;2325967113486441.

[16] Kung J, Chiappelli F, Cajulis OO, Avezova R, Kossan G, Chew L, et al. From systematic reviews to clinical recommendations for evidence-based health care: validation of Revised Assessment of Multiple Systematic Reviews (R-AMSTAR) for grading of clinical relevance. Open Dent J 2010;4:84–91.

[17] Moher D, Liberati A, Tetzlaff J, Altman DG. Preferred Reporting Items for Systematic Reviews and Meta-Analyses: The PRISMA Statement. Int J Surg 2009;8:336–41.

[18] Detsky AS, Naylor CD, O'Rourke K, McGeer AJ, L'Abbé KA. Incorporating variations in the quality of individual randomized trials into meta-analysis. J Clin Epidemiol 1992;45:255–65.

[19] Slim K, Nini E, Forestier D, Kwiatkowski F, Panis Y, Chipponi J. Methodological Index for Non-Randomized Studies (MINORS): development and validation of a new instrument. ANZ J Surg 2003;73:712–6.

[20] Koo TK, Li MY. A guideline of selecting and reporting intraclass correlation coefficients for reliability research. J Chiropr Med 2016;15:155–63.

[21] Dulai SK, Slobogean BLT, Beauchamp RD, Mulpuri K. A quality assessment of randomized clinical trials in pediatric orthopaedics. J Pediatr Orthop 2007;27:573–81.

[22] Horner NS, Moroz PA, Bhullar R, Habib A, Simunovic N, Wong I, et al. Open versus arthroscopic Latarjet procedures for the treatment of shoulder instability: a systematic review of comparative studies. BMC Musculoskelet Disord 2018;19:255.

[23] Freeman MF, Tukey JW.Transformations related to the angular and the square root. Ann Math Stat 1950;21:607–11.

[24] DerSimonian R, Laird N. Meta-analysis in clinical trials. Control Clin Trials 1986;7:177–88.

[25] Miller JJ. The inverse of the Freeman-Tukey double arcsine transformation. Am Stat 1978;32:138.

[26] Higgins JPT, Thompson SG. Quantifying heterogeneity in a meta-analysis. Stat Med 2002;21:1539–58.

[27] Achtnich A, Stiepani H, Forkel P, Metzlaff S, Hänninen EL, Petersen W. Tunnel widening after anatomic double-bundle and mid-position single-bundle anterior cruciate ligament reconstruction. Arthroscopy 2013;29:1515–24.

[28] Shimodaira H, Tensho K, Akaoka Y, Takanashi S, Kato H, Saito N. Remnant-preserving tibial tunnel positioning using anatomic landmarks in double-bundle anterior cruciate ligament reconstruction. Arthroscopy 2016;32:1822–30.

[29] Sahasrabudhe A, Christel P, Anne F, Appleby D, Basdekis G. Postoperative evaluation of tibial footprint and tunnels characteristics after anatomic double-bundle anterior cruciate ligament reconstruction with anatomic aimers. Knee Surg Sports Traumatol Arthrosc 2010;18:1599–606.

[30] Onodera J, Yasuda K, Masuda T, Tanabe Y, Kitamura N, Yagi T, et al. Is the grafted tendon shifted anteriorly in the femoral tunnel at the postremodeling phase after anterior cruciate ligament reconstruction? A clinical MRI study. Orthop J Sports Med 2017;5:2325967117711120.

[31] Naraoka Y, Kimura Y, Tsuda E, Yamamoto Y, Ishibashi Y. Does remnant preservation influence tibial tunnel enlargement or graft-to-bone integration after double-bundle anterior cruciate ligament reconstruction using hamstring autografts and suspensory fixation? A computed tomography and magnetic resonance imaging evaluation. Orthop J Sports Med 2018;6:2325967118790238.

[32] Masuda T, Kondo E, Onodera J, Kitamura N, Inoue M, Nakamura E, et al. Effects of remnant tissue preservation on tunnel enlargement after anatomic double-bundle anterior cruciate ligament reconstruction using the hamstring tendon. Orthop J Sports Med 2018;6:2325967118811293.

[33] Lu W, Wang D, Zhu W, Li D, Ouyang K, Peng L, et al. Placement of double tunnels in ACL reconstruction using bony landmarks versus existing footprint remnant: a prospective clinical study with 2-year follow-up. Am J Sports Med 2015;43:1206–14.

[34] Lee YS, Lee BK, Moon DH, Park HG, Kim WS, Moon CW. Comparison of tunnel locations of double bundle ACL reconstruction using the conventional transtibial technique with anatomic tunnel locations using a 3D CT model. Arch Orthop Trauma Surg 2013;133:1121–8.

[35] Lee HM, Lee LS, Hung ST, Shih JT, Ho YJ. Functional outcome of double-bundle anterior cruciate ligament reconstruction. Formos J Musculoskelet Disord 2012;3:88–93.

[36] Kim JG, Wang JH, Lim HC, Ahn JH. Femoral graft bending angle and femoral tunnel geometry of transportal and outside-in techniques in anterior cruciate ligament reconstruction: an in vivo 3-dimensional computed tomography analysis. Arthroscopy 2012;28:1682–94.

[37] Kim DS, Yi CH, Chung HJ, Yoon YS. Clinical results of technique for double bundle anterior cruciate ligament reconstruction using hybrid femoral fixation and Retroscrew. Clin Orthop Surg 2011;3:285–94.

[38] Kiekara T, Paakkala A, Suomalainen P, Huhtala H, Järvelä T. Femoral and tibial tunnel diameter and bioabsorbable screw findings after double-bundle ACL reconstruction in 5-year clinical and MRI follow-up. Orthop J Sports Med 2017;5:2325967116685525.

[39] Kiekara T, Järvelä T, Huhtala H, Moisala AS, Suomalainen P, Paakkala A. Tunnel communication and increased graft signal intensity on magnetic resonance imaging of double-bundle anterior cruciate ligament reconstruction. Arthroscopy 2014;30:1595–601.

[40] Kambara S, Nakayama H, Yamaguchi M, Matsumoto A, Sasaki K, Kashiwa K, et al. Comparison of transportal and outside-in techniques for posterolateral femoral tunnel drilling in double-bundle ACL reconstruction- three-dimensional CT analysis of bone tunnel geometry. J Orthop Sci 2017;22:481–7.

[41] Joshi D, Jain V, Goyal A, Bahl V, Modi P, Chaudhary D. Outcome of double bundle anterior cruciate ligament reconstruction using crosspin and aperture fixation. Indian J Orthop 2014;48:42–8.

[42] Järvelä T, Moisala AS, Paakkala T, Paakkala A. Tunnel enlargement after double-bundle anterior cruciate ligament reconstruction: a prospective, randomized study. Arthroscopy 2008;24:1349–57.

[43] Ichiba A, Tokuyama F, Makuya K, Oda K. Graft quality and clinical outcomes of intraoperative bone tunnel communication in anatomic double-bundle anterior cruciate ligament reconstruction. Asia Pac J Sports Med Arthrosc Rehabil Technol 2016;3:6–12.

[44] Hofbauer M, Valentin P, Kdolsky R, Ostermann RC, Graf A, Figl M, et al. Rotational and translational laxity after computer-navigated single- and double-bundle anterior cruciate ligament reconstruction. Knee Surg Sports Traumatol Arthrosc 2010;18:1201–7.

[45] Hantes ME, Liantsis AK, Basdekis GK, Karantanas AH, Christel P, Malizos KN. Evaluation of the bone bridge between the bone tunnels after anatomic double-bundle anterior cruciate ligament reconstruction. Am J Sports Med 2010;38:1618–25.

[46] Falconer TM, Gohil S, Tusak L, Breidahl WH, Annear PT. Tunnel positioning in remnant sparing double bundle ACL reconstruction – a 2-year study of MRI tunnel positions, clinical outcomes and tunnel confluence. J Musculoskelet Res 2016;19:165004.

[47] Chiang ER, Chen KH, Lin ACC, Wang ST, Wu HT, Ma HL, et al. Comparison of tunnel enlargement and clinical outcome between bioabsorbable interference screws and cortical button-post fixation in arthroscopic double-bundle anterior cruciate ligament reconstruction: a prospective randomized study with a minimum follow-up of 2 years. Arthroscopy 2019;35:544–51.

[48] Beyaz S, Güler ÜÖ, Demir Ş, Yüksel S, Çınar BM, Özkoç G, et al. Tunnel widening after single- versus double-bundle anterior cruciate ligament reconstruction: a randomized 8-year follow-up study. Arch Orthop Trauma Surg 2017;137:1547–55.

[49] Aglietti P, Giron F, Losco M, Cuomo P, Ciardullo A, Mondanelli N. Comparison between single- and double-bundle anterior cruciate ligament reconstruction: a prospective, randomized, single-blinded clinical trial. Am J Sports Med 2010;38:25–34.

[50] Aga C, Wilson KJ, Johansen S, Dornan G, La Prade RF, Engebretsen L. Tunnel widening in single- versus double-bundle anterior cruciate ligament reconstructed knees. Knee Surg Sports Traumatol Arthrosc 2017;25:1316-27.

[51] Siebold R. Observations on bone tunnel enlargement after double-bundle anterior cruciate ligament reconstruction. Arthroscopy 2007;23:291–8.

[52] Taketomi S, Inui H, Yamagami R, Shirakawa N, Kawaguchi K, Nakagawa T, et al. Bone-patellar tendon-bone autograft versus hamstring tendon autograft for anatomical anterior cruciate ligament reconstruction with three-dimensional validation of femoral and tibial tunnel positions. J Knee Surg 2018;31:866–74.

[53] Taketomi S, Nakagawa T, Takeda H, Nakajima K, Nakayama S, Fukai A, et al. Anatomical placement of double femoral tunnels in anterior cruciate ligament reconstruction: anteromedial tunnel first or posterolateral tunnel first?. Knee Surg Sports Traumatol Arthrosc 2011;19:424–31.

[54] Tashiro Y, Okazaki K, Uemura M, Toyoda K, Osaki K, Matsubara H, et al. Comparison of transtibial and transportal techniques in drilling femoral tunnels during anterior cruciate ligament reconstruction using 3D-CAD models. Open Access J Sports Med 2014;5:65–72.

[55] Tomihara T, Yoshida G, Hara Y, Taniuchi M, Shimada N. Transparent 3-dimensional CT in evaluation of femoral bone tunnel communication after ACL double-bundle reconstruction: comparison between outside-in and transportal technique. Knee Surg Sports Traumatol Arthrosc 2014;22:1563–72.

[56] Wang JH, Kim JG, Ahn JH, Lim HC, Hoshino Y, Fu FH. Is femoral tunnel length correlated with the intercondylar notch and femoral condyle geometry after double-bundle anterior cruciate ligament

reconstruction using the transportal technique? An in vivo computed tomography analysis. Arthroscopy 2012;28:1094–103.

[57] Wang JH, Lee ES, Lee BH. Paradoxical tunnel enlargement after ACL reconstruction with hamstring autografts when using β-TCP containing interference screws for tibial aperture fixation-prospectively comparative study. BMC Musculoskelet Disord 2017;18:398.

[58] Zaffagnini S, Muccioli GMM, Signorelli C, Lopomo N, Grassi A, Bonanzinga T, et al. Anatomic and nonanatomic double-bundle anterior cruciate ligament reconstruction: an in vivo kinematic analysis. Am J Sports Med 2014;42:708–15.

[59] Zhu W, Lu W, Han Y, Hui S, Ou Y, Peng L, et al. Application of a computerised navigation technique to assist arthroscopic anterior cruciate ligament reconstruction. Int Orthop 2013;37:233-8.

[60] L'Insalata JC, Klatt B, Fu FH, Harner CD. Tunnel expansion following anterior cruciate ligament reconstruction: a comparison of hamstring and patellar tendon autografts. Knee Surg Sports Traumatol Arthrosc 1997;5:234–8.

[61] Offerhaus C, Albers M, Nagai K, Arner JW, Höher J, Musahl V, et al. Individualized anterior cruciate ligament graft matching: in vivo comparison of cross-sectional areas of hamstring, patellar, and quadriceps tendon grafts and ACL insertion area. Am J Sports Med 2018;46:2646–52.

[62] Ahn JH, Kim S, Kim J. Is intraoperative fluoroscopy necessary in anterior cruciate ligament double-bundle reconstruction? A prospective randomized controlled trial. Orthop Traumatol Surg Res 2019;105:1093-1099.

[63] Lind M, Feller J, Webster KE. Bone tunnel widening after anterior cruciate ligament reconstruction using EndoButton or EndoButton continuous loop. Arthroscopy 2009;25:1275–80.

[64] Vadalà A, Iorio R, De Carli A, Argento G, Sanzo V Di, Conteduca F. The effect of accelerated, brace free, rehabilitation on bone tunnel enlargement after ACL reconstruction using hamstring tendons: a CT study. Knee Surg Sports Traumatol Arthrosc 2007;15:365–71.

[65] Xu Y, Ao Y, Wang J, Yu J, Cui G. Relation of tunnel enlargement and tunnel placement after single-bundle anterior cruciate ligament reconstruction. Arthroscopy 2011;27:923–32.

[66] Furumatsu T, Hiranaka T, Kodama Y, Kamatsuki Y, Okazaki Y, Yamawaki T, et al. Intraarticular lengths of double-bundle grafts can change during knee flexion: Intraoperative measurements in anatomic anterior cruciate ligament reconstructions. Orthop Traumatol Surg Res 2021;107:102816.

[67] Marchant BG, Noyes FR, Barber-Westin SD, Fleckenstein C. Prevalence of nonanatomical graft placement in a series of failed anterior cruciate ligament reconstructions. Am J Sports Med 2010;38:1987–96.

[68] Parkar AP, Adriaensen MEAPM, Fischer-Bredenbeck C, Inderhaug E, Strand T, Assmus J, et al. Measurements of tunnel placements after anterior cruciate ligament reconstruction — A comparison between CT, radiographs and MRI. Knee 2015;22:574–9.

[69] Ducouret E, Loriaut P, Boyer P, Perozziello A, Pesquer L, Mounayer C, et al. Tunnel positioning assessment after anterior cruciate ligament reconstruction at 12 months: Comparison between 3D CT and 3D MRI. A pilot study. Orthop Traumatol Surg Res 2017;103:937-942.

[70] Hoser C, Tecklenburg K, Kuenzel KH, Fink C. Postoperative evaluation of femoral tunnel position in ACL reconstruction: plain radiography versus computed tomography. Knee Surg Sports Traumatol Arthrosc 2005;13:256–62.

[71] Vasudeva V, Key S, Phillips A, Kahane S, Stevens J, Wall C, et al. Evaluation of a novel lower radiation computed tomography protocol for assessment of tunnel position post anterior cruciate ligament reconstruction. BMC Med Imaging 2020;20:82.

[72] Meuffels DE, Potters JW, Koning AH, Brown CH Jr, Verhaar JA, Reijman M. Visualization of postoperative anterior cruciate ligament reconstruction bone tunnels: Reliability of standard radiographs, CT scand, and 3D virtual reality images. Acta Orthop 2011;82:699-703.

[73] Hwang DH, Shetty GM, Kim JI, Kwon JH, Song JK, Muñoz M, et al. Does press-fit technique reduce tunnel volume enlargement after anterior cruciate ligament reconstruction with autologous hamstring tendons? A prospective randomized computed tomography study. Arthroscopy 2013;29:83–8.

Study	Level of evidence	Country	Enrolled patients	Age (yr)	M/F	Mean follow-up time (mo)	Reported incidence of tibial and/or femoral tunnel coalition (T/F/Both)	Detsky score (Y.N.)	MINORS score (Y.N.)
Achtnich (2013)	III	Germany	21	35±10	10/11	8 (6.8-8.3)	Both		17/24
Aga (2017)	III	Norway	20	25.5 (19-37)	16/4	366 (333-460)	Both		22/24
Aglietti (2010)	I	Italy	35	28 (16-40)	28/7	NR (24-)	F	18/20	
Beyaz (2017)	II	Germany	15	33.53±5.47	15/0	96	T	17/20	
Chiang (2019)	II	Taiwan	Bioabsorbable interference screw: 29 Cortical button: 28	Bioabsorbable interference screw: 30.3±6.9 Cortical button: 29.5±5.7	Bioabsorbable interference screw: 28/1 Cortical button: 26/2	NR (24-)	Both	17/20	
Falconer (2016)	IV	Australia	44	30.9±11.8	18/26	NR (24-46.8)	Both		10/16
Hantes (2010)	IV	Greece	32	23.5 (18-28)	32/0	17.3 (14-36)	Both		12/16
Hofbauer (2010)	III	Austria	28	34.8 (17.4-57.4)	18/10	43 (27.2-49.3)	Both		17/24
Ichiba (2016)	IV	Japan	52	30.7 (13-60)	34/18	NR (12-)	Both		14/16
Järvelä (2008)	I	Finland	35	35±10	24/11	27 (24-36)	Both	18/20	
Joshi (2014)	IV	India	100	33.1 (18-45)	64/36	NR (12-)	F		11/16
Kambara (2017)	III	Japan	Transportal: 20 Outside-in: 20	Transportal: 18.6±6.1 (13-42) Outside-in: 25±7.3 (16-39)	Transportal: 6/14 Outside-in: 15/5	NR	F		18/24
Kawaguchi (2013)	IV	Japan	39	26.4±12.8	19/20	NR (12-25)	Both		14/16
Kiekara (2014)	IV	Finland	59	35	42/17	22 (16-29)	Both		14/16
Kiekara (2014)	IV	Finland	66	35	49/17	NR	Both		9/16
Kiekara (2017)	IV	Finland	66	NR	NR	NR (24-60)	Both		10/16
Kim (2011)	IV	South Korea	47	23.8 (19-38)	46/1	18.7 (12-23)	T		11/16
Kim (2012)	I	South Korea	Transportal: 21 Outside-in: 18	Transportal: 36.7±10.3 (18-47) Outside-in: 30±12.2 (17-54)	Transportal: 18/3 Outside-in: 14/4	NR	F	18/20	
Lee (2012)	IV	Taiwan	20	22.7 (18-29)	15/5	16 (12-26)	Both		12/16
Lee (2013)	IV	South Korea	28	27.6 (19-42)	NR	NR	T		15/16
Lu (2015)	II	China	Bony landmark: 36 Footprint: 36	Bony landmark: 31.4±3.1 Footprint: 29.3±2.4	NR	39.6	Both	18/20	
Masuda (2018)	II	Japan	Remnant resecting: 39 Remnant preserve: 40	Remnant resecting: 29±14 Remnant preserve: 30±13	Remnant resecting: 20/19 Remnant preserve: 18/22	34.7 (12-16)	Both		21/24
Naraoka (2018)	II	Japan	Non-remnant: 25 Remnant preserve: 23	Non-remnant: 21.2±8.3 Remnant preserve: 28.8±12.5	Non-remnant: 11/14 Remnant preserve: 8/15	NR	T		24/24
Onodera (2017)	IV	Japan	20	Sub-study 1: 25.4±12.5	Sub-study 1: 11/9	NR (12-18)	F		12/16
Sahasrabudhe (2010)	IV	United States of America	38	NR	NR	NR	T		11/16
Shimodaira (2016)	III	Japan	Anatomic DB: 50 Non-anatomic DB: 54	Anatomic DB: 26±10.3 (14-52) Non-anatomic DB: 24.9±10.1 (12-55)	Anatomic DB: 17/33 Non-anatomic DB: 24/30	NR	T		17/24
Siebold (2007)	IV	Germany	22	28 (15-42)	20/2	12.3 (0-16)	Both		12/16
Siebold (2010)	IV	Germany	21	29 (17-59)	14/7	7	Both		13/16
Taketomi (2011)	III	Japan	Anteromedial portal first: 17 Posterolateral portal first: 17	Anteromedial portal first: 31±13 (15-63) Posterolateral portal first: 31±11 (17-51)	Anteromedial portal first: 12/5 Posterolateral portal first: 9/8	NR	F		18/24
Taketomi (2018)	III	Japan	23	32 (15-55)	6/17	25 (24-36)	Both		21/24
Tashiro (2014)	III	Japan	Transtibial: 11 Trans-anteromedial portal: 25	30 (13-48)	24/12	NR	F		20/24
Tomihara (2014)	III	Japan	Outside-in: 25 Transportal: 30	Outside-in: 25.1±10.7 Transportal: 25.1±9.8	Outside-in: 12/13 Transportal: 19/11	NR	Both		20/24
Wang (2012)	IV	South Korea	29	32±10.8 (15-55)	28/1	NR	F		10/16
Wang (2017)	II	South Korea	PLLA: 28 βTCP: 29	PLLA: 36.1±8.9 (20-60) βTCP: 32.7±12.3 (20-60)	PLLA: 21/7 βTCP: 24/5	33 (24-60)	T		23/24
Zaffagnini (2014)	II	Italy	Anatomic DB: 13 Non-anatomic DB: 13	Anatomic DB: 32±8 Non-anatomic DB: 29±7	Anatomic DB: 11/2 Non-anatomic DB: 12/1	NR	Both		21/24
Zhu (2013)	III	China	22	29 (19.2±43.7)	12/10	31.3 (25.2-49)	Both		19/24

Table 1.

Study	Femoral tunnel creation technique	Fixation method	Diagnostic modality	Location of tunnel coalition	Follow-up period of first tunnel evaluation	Follow-up period of second tunnel evaluation (if applicable)
Achtnich (2013)	Transportal	Extracortical fixation - Femur Interference screw and extracortical fixation - Tibia	MRI	Intra-articular aperture	1-2dy	8mo
Aga (2017)	Transportal	Closed loop EndoButton - Femur Non-absorbable interference screw - Tibia	CT	Intra-articular aperture. Distance from intra-articular aperture to cortical bridge was between 2.7 and 15.2 mm	1dy	12mo
Aglietti (2010)	Outside-in	Interference screw/staple - Femur Bony or metallic bridge - Tibia	Arthroscopy	intra-articular aperture		
Beyaz (2017)	Transportal	Closed loop EndoButton - Femur Hydroxyapatite interference screw/staple - Tibia	CT	Intra-articular aperture	2mo, 3mo, 6mo	96mo
Chiang (2019)	Transportal	Bioabsorbable interference screw/Cortical button	MRI	N/A	25.9mo (24.3mo-31.3mo)	
Falconer (2016)	Transportal	Closed loop EndoButon- Femur Interference screw-Tibia	MRI	Intra-articular aperture	12mo	24mo
Hantes (2010)	Transportal	Closed loop EndoButton - Femur Interference screw - Tibia	CT	intra-articular aperture	17.3mo (14mo-26mo)	
Hofbauer (2010)	Transtibial	Closed loop EndoButton - Femur Suture disc - Tibia	Radiography		Immediately	24mo
Ichiba (2016)	Outside-in	Closed loop EndoButton - Femur Double-Spike Plates - Tibia	CT	N/A	10dy	
Järvelä (2008)	Transportal	Bioabsorbable interference screw	MRI	Mean length of bone tunnel communication. Tibia: 9.3 ± 8.2 mm (range, 5.0-18.6 mm). Femur: N/A	27mo	
Joshi (2014)	AM- Transtibial, PL Transportal	Bioabsorbable interference screw - Femur Bioabsorbable interference screw/Crosspin - Tibia	Arthroscopy	N/A	Intraoperative	
Kambara (2017)	Transportal Outside-in	Bioabsorbable interference screw - Femur Screw post - Tibia	CT	Intra-articular aperture	1wk	
Kawaguchi (2013)	Transtibial	Closed loop EndoButton/Spiked staples	CT	Serial sections along femoral tunnel.	2wk	12mo
Kiekara (2014)	Transportal	Bioabsorbable interference screws	MRI	Femur: Intra-articular aperture, Tibia: Intra-articular and 10mm from intra-articular aperture	24mo	
Kiekara (2014)	Transportal	Bioabsorbable interference screws	MRI	From intra-articular aperture to 10mm from aperture	22mo (16mo-29mo)	
Kiekara (2017)	Transportal	Bioabsorbable interference screws	MRI	From intra-articular aperture to 10mm from aperture	24mo	60mo
Kim (2011)	Outside-in	Closed loop Endobutton - Femur Retrowscrew/staples/spiked washer screw - Tibia	Arthroscopy	From intra-articular aperture to 10mm from aperture	Intraoperative	
Kim (2012)	Transportal Outside-in	Closed loop EndoButton - Femur Bioabsorbable interference screw - Tibia	CT	Intra-articular aperture		
Lee (2012)	Transtibial	EndoButton CL+ Bioabsorbable interference screw- Femur Screw and washer- Tibia	MRI	Intra-articular aperture	6mo	
Lee (2013)	Transtibial	RigidFix - Femur Bioabsorbable interference screw/Biotenodesis screw - Tibia	CT	Intra-articular aperture: bone bridge thickness and height from the union	(2wk-1mo)	
Lu (2015)	Transportal	Closed loop EndoButton - Femur Hydroxyapatite interference screw - Tibia	CT	N/A	Immediately	
Masuda (2018)	Transtibial	Closed loop EndoButton - Femur Spiked staples - Tibia	CT	Intra-articular aperture	2wk	12mo
Naraoka (2018)	Transportal	Closed loop EndoButton - Femur Mini-suture disc - Tibia	CT/MRI	10 mm from the joint surface	1wk	12mo
Onodera (2017)	Transtibial	Closed loop EndoButton/Staples	CT/MRI	Intra-articular aperture: Femur only	2wk	12mo
Sahasrabudhe (2010)	Transportal	Closed loop EndoButton - Femur Bioabsorbable interference screw - Tibia	CT	Intra-articular aperture	3dy	
Shimodaira (2016)	N/A		CT	Intra-articular aperture	2wk	
Siebold (2007)	AM- Transtibial, PL Transportal	Closed loop EndoButton - Femur Bioabsorbable interference screw - Tibia	MRI	Intra-articular aperture	12mo	
Siebold (2010)	Transportal	Closed-loop EndoButton - Femur Suture bone bridge/bone block fixation - Tibia	MRI	Level of the joint line up to 1 cm to the joint line	2dy	7mo
Taketomi (2011)	Transportal	EndoButton CL- Femur, No data- Tibia	CT	Intra-articular aperture	1wk	
Taketomi (2018)	Transportal	EndoButton CL- Femur double spike plates (DSPs)+ half threaded 5.0-mm cancellous screws- Tibia	CT	Intra-articular aperture		
Tashiro (2014)	Transtibial Transportal	N/A	CT	Intra-articular aperture	2wk	
Tomihara (2014)	Transportal Outside-in	Closed loop EndoButton - Femur Double-Spike Plates - Tibia	CT	Intra-articular aperture	1wk	6mo
Wang (2012)	Transportal	N/A	CT	Intra-articular aperture	Immediately	
Wang (2017)	Transportal and outside-in	Closed loop cortical suspenson - Femur PLLA bioabsorbable interference screw/βTCP bioabsorbable interference screw - Tibia	CT	Intra-articular aperture	Immediately	
Zaffagnini (2014)	Transportal	Closed loop EndoButton - Femur Bioabsorbable interference screw - Tibia	Arthroscopy	N/A	Immediately	
Zhu (2013)	Transtibial	Closed loop EndoButton - Femur Bioabsorbable interference screw - Tibia	CT/Radiography	N/A	Immediately	

Table 2.

Figure legends

Fig. 1. PRISMA flow diagram of the screening process for literature on tunnel coalition in DB ACLR using hamstring graft

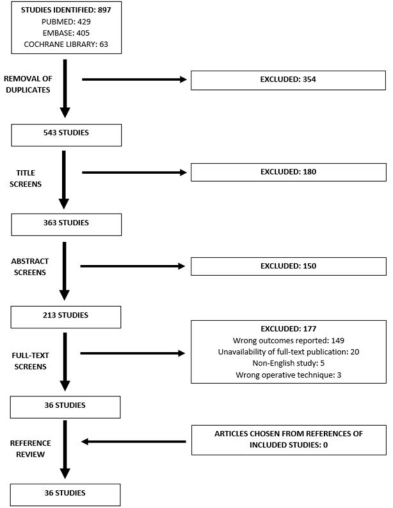
Fig. 2. Forest plot indicating the rate of femoral coalition at final follow-up within each of the included studies reported as proportion of means

Fig. 3. Forest plot indicating the rate of tibial coalition at final follow-up within each of the included studies reported as proportion of patients

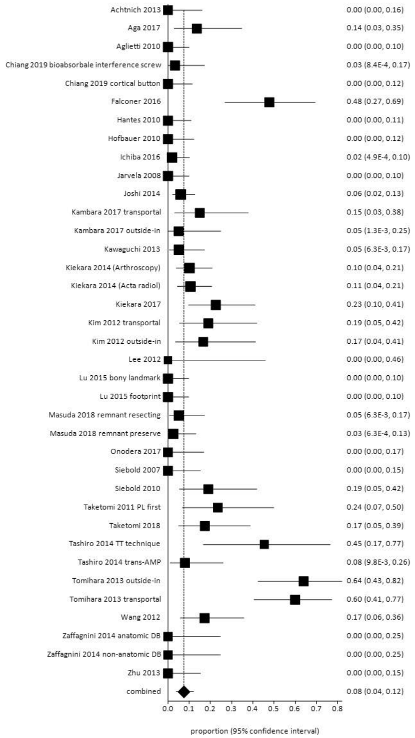
Table legends

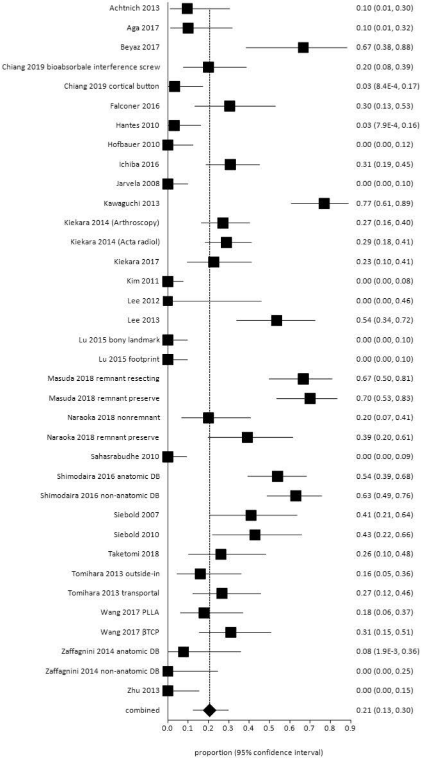
Table 1 Characteristics of included studies

Table 2 Operative techniques, diagnostic modalities, and tunnel coalition details



STUDIES IDENTIFIED: 897
PUBMED: 429
EMBASE: 405
COCHRANE LIBRARY: 63
REMOVAL OF DUPLICATES
EXCLUDED: 354
543 STUDIES
TITLE SCREENS
EXCLUDED: 180
363 STUDIES
ABSTRACT SCREENS
EXCLUDED: 150
213 STUDIES
FULL-TEXT SCREENS
EXCLUDED: 177
Wrong outcomes reported: 149
Unavailability of full-text publication: 20
Non-English study: 5
Wrong operative technique: 3
36 STUDIES
REFERENCE REVIEW
ARTICLES CHOSEN FROM REFERENCES OF INCLUDED STUDIES: 0
36 STUDIES


Achtnich 2013 0.00 (0.00, 0.16)
Aga 2017 0.14 (0.03, 0.35)
Aglietti 2010 0.00 (0.00, 0.10)
Chiang 2019 bioabsorbale interference screw 0.03 (8.4E-4, 0.17)
Chiang 2019 cortical button 0.00 (0.00, 0.12)
Falconer 2016 0.48 (0.27, 0.69)
Hantes 2010 0.00 (0.00, 0.11)
Hofbauer 2010 0.00 (0.00, 0.12)
Ichiba 2016 0.02 (4.9E-4, 0.10)
Jarvela 2008 0.00 (0.00, 0.10)
Joshi 2014 0.06 (0.02, 0.13)
Kambara 2017 transportal 0.15 (0.03, 0.38)
Kambara 2017 outside-in 0.05 (1.3E-3, 0.25)
Kawaguchi 2013 0.05 (6.3E-3, 0.17)
Kiekara 2014 (Arthroscopy) 0.10 (0.04, 0.21)
Kiekara 2014 (Acta radiol) 0.11 (0.04, 0.21)
Kiekara 2017 0.23 (0.10, 0.41)
Kim 2012 transportal 0.19 (0.05, 0.42)
Kim 2012 outside-in 0.17 (0.04, 0.41)
Lee 2012 0.00 (0.00, 0.46)
Lu 2015 bony landmark 0.00 (0.00, 0.10)
Lu 2015 footprint 0.00 (0.00, 0.10)
Masuda 2018 remnant resecting 0.05 (6.3E-3, 0.17)
Masuda 2018 remnant preserve 0.03 (6.3E-4, 0.13)
Onodera 2017 0.00 (0.00, 0.17)
Siebold 2007 0.00 (0.00, 0.15)
Siebold 2010 0.19 (0.05, 0.42)
Taketomi 2011 PL first 0.24 (0.07, 0.50)
Taketomi 2018 0.17 (0.05, 0.39)
Tashiro 2014 TT technique 0.45 (0.17, 0.77)
Tashiro 2014 trans-AMP 0.08 (9.8E-3, 0.26)
Tomihara 2013 outside-in 0.64 (0.43, 0.82)
Tomihara 2013 transportal 0.60 (0.41, 0.77)
Wang 2012 0.17 (0.06, 0.36)
Zaffagnini 2014 anatomic DB 0.00 (0.00, 0.25)
Zaffagnini 2014 non-anatomic DB 0.00 (0.00, 0.25)
Zhu 2013 0.00 (0.00, 0.15)
combined 0.08 (0.04, 0.12)
0.0 0.1 0.2 0.3 0.4 0.5 0.6 0.7 0.8
proportion (95% confidence interval)


Achtnich 2013
0.10 (0.01, 0.30)
Aga 2017
0.10 (0.01, 0.32)
Beyaz 2017
0.67 (0.38, 0.88)
Chiang 2019 bioabsorbale interference screw
0.20 (0.08, 0.39)
Chiang 2019 cortical button
0.03 (8.4E-4, 0.17)
Falconer 2016
0.30 (0.13, 0.53)
Hantes 2010
0.03 (7.9E-4, 0.16)
Hofbauer 2010
0.00 (0.00, 0.12)
Ichiba 2016
0.31 (0.19, 0.45)
Jarvela 2008
0.00 (0.00, 0.10)
Kawaguchi 2013
0.77 (0.61, 0.89)
Kiekara 2014 (Arthroscopy)
0.27 (0.16, 0.40)
Kiekara 2014 (Acta radiol)
0.29 (0.18, 0.41)
Kiekara 2017
0.23 (0.10, 0.41)
Kim 2011
0.00 (0.00, 0.08)
Lee 2012
0.00 (0.00, 0.46)
Lee 2013
0.54 (0.34, 0.72)
Lu 2015 bony landmark
0.00 (0.00, 0.10)
Lu 2015 footprint
0.00 (0.00, 0.10)
Masuda 2018 remnant resecting
0.67 (0.50, 0.81)
Masuda 2018 remnant preserve
0.70 (0.53, 0.83)
Naraoka 2018 nonremnant
0.20 (0.07, 0.41)
Naraoka 2018 remnant preserve
0.39 (0.20, 0.61)
Sahasrabudhe 2010
0.00 (0.00, 0.09)
Shimodaira 2016 anatomic DB
0.54 (0.39, 0.68)
Shimodaira 2016 non-anatomic DB
0.63 (0.49, 0.76)
Siebold 2007
0.41 (0.21, 0.64)
Siebold 2010
0.43 (0.22, 0.66)
Taketomi 2018
0.26 (0.10, 0.48)
Tomihara 2013 outside-in
0.16 (0.05, 0.36)
Tomihara 2013 transportal
0.27 (0.12, 0.46)
Wang 2017 PLLA
0.18 (0.06, 0.37)
Wang 2017 βTCP
0.31 (0.15, 0.51)
Zaffagnini 2014 anatomic DB
0.08 (1.9E-3, 0.36)
Zaffagnini 2014 non-anatomic DB
0.00 (0.00, 0.25)
Zhu 2013
0.00 (0.00, 0.15)
combined
0.21 (0.13, 0.30)
0.0 0.1 0.2 0.3 0.4 0.5 0.6 0.7 0.8 0.9
proportion (95% confidence interval)