Comparison of femoral tunnel length and obliquity of anatomic versus nonanatomic anterior cruciate ligament reconstruction: A meta-analysis

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Abstract

Purpose
Theoretical considerations suggest that femoral tunnel length might cause graft mismatch, and femoral tunnel obliquity could be related to the longevity of graft in anterior cruciate ligament (ACL) reconstruction. However, controversy still exists regarding these issues in the context of the comparison of anatomic and nonanatomic ACL reconstructions. The purpose of this meta-analysis was to compare the length and obliquity of the femoral tunnel created by drilling through either anatomic or nonanatomic ACL reconstructions.

Materials and method
In this meta-analysis, we reviewed studies that compared femoral tunnel length and femoral tunnel obliquity in the coronal plane with the use of anatomic or nonanatomic ACL reconstruction. The major databases were reviewed for appropriate studies from the earliest available date of indexing through December 31, 2018. No restrictions were placed on the language of publication.

Results
Twenty-seven studies met the criteria for inclusion in this meta-analysis. The femur tunnel length of anatomic ACL reconstruction was significantly shorter compared with that of nonanatomic ACL reconstruction by 8.66 mm (95% CI: 7.10–10.22 mm; P < 0.001), while the femur tunnel obliquity in the coronal plane of anatomic ACL reconstruction was significantly more oblique versus that of nonanatomic ACL reconstruction by 15.29˚ (95% CI: 8.07˚–22.52˚; P < 0.001). Similar results in terms of femoral tunnel length were found for the sub-group with cadaveric (7.15 mm; 95% CI: 2.69–11.61 mm; P = 0.002) and noncadaveric (8.96 mm; 95% CI: 7.24–10.69 mm; P < 0.001) studies, whereas different results in terms of
femoral tunnel obliquity were noted for the subgroup with cadaveric (10.62˚; 95% CI: −6.12˚ to 27.37˚; P = 0.21) and noncadaveric (15.86˚; 95% CI: 8.11˚–23.60˚; P < 0.001) studies.

Conclusion

Anatomic ACL reconstruction resulted in the femoral tunnel length and femoral tunnel obliquity in the coronal plane being shorter and more oblique, respectively, as compared with nonanatomic ACL reconstruction.

Level of evidence

Therapeutic study, Level III.

Introduction

The goal of anterior cruciate ligament (ACL) reconstruction is to provide the patient with a graft that replicates the normal kinematics of the knee.[1,2] As a result of the desire to reproduce normal kinematics of the knee during the creation of the ACL femoral tunnel, arthroscopic ACL reconstruction has evolved from a transtibial (TT) technique to anteromedial (AM) portal or outside-in (OI) technique despite the fact that OI technique mostly predated TT technique; TT technique evolved from OI technique as a way to perform arthroscopic ACL reconstructions more easily. OI technique came back into favor and AM portal technique became more popular with an attempt to place the femoral tunnel within the footprint.[3–5] Thus, most studies have focused predominantly on illustrating the femoral tunnel location in order to show the superiority of reproducing ACL footprints in anatomical reconstructions in comparison with those in TT techniques. However, femoral tunnel length and femoral tunnel obliquity have clinically important relevance because the former might also cause the problem of graft mismatch and the latter could be related to graft longevity.[6–8] It has been well-established through previous studies that the AM portal or OI technique, one of the anatomic ACL reconstruction options, results in a shorter femoral tunnel than does the TT technique.[9,10] These findings are of clinical relevance in that such can lead to the problem of graft incorporation and stability due to a reduced length of graft within the femoral tunnel at the time of reconstruction.[11,12] In addition, biomechanical studies have supported a more oblique femoral tunnel position in the coronal plane because of a decrease in tension across the graft, increased range of motion, and reduced posterior cruciate ligament (PCL) impingement.[13,14] Also, one previous study on the association between graft-bending angle and computed tomography (CT) plane found that OI technique had a significantly larger coronal bending angle than the AM portal technique, but not in the axial and sagittal planes.[10] Importantly, controversy still exists regarding femur tunnel obliquity with respect to the results of measurement values between anatomic and nonanatomic ACL reconstructions. Although many studies have been published to date focusing on single-bundle and double-bundle ACL reconstruction, few comparative studies assessing femoral tunnel length and femoral tunnel obliquity between anatomic and nonanatomic ACL reconstructions have been completed at this time.

It is still controversial which of these methods is appropriate to achieve proper femoral tunnel length and obliquity. In addition, investigation of these parameters was deemed to be important because they could determine the longevity of graft in ACL reconstruction. The
Purpose of this meta-analysis was to determine the length of the femoral tunnel created by drilling through either anatomic or nonanatomic ACL reconstructions. Additionally, we sought to determine the obliquity of a femoral tunnel when placed through anatomic or nonanatomic ACL reconstructions.

Materials and methods

This meta-analysis was conducted according to the guidelines of the preferred reporting items for systematic reviews and meta-analysis (PRISMA) statement (S1 PRISMA Checklist).

Data and literature sources

We performed an electronic records search in the MEDLINE (Inception to December 2018), EMBASE (Inception to December 2018), Cochrane Library (Inception to December 2018), and KoreaMed (Inception to December 2018) databases.

Study selection

Based on the title and abstract, two reviewers independently selected relevant studies for further review. Each reviewer reviewed one database, which in turn was validated twice by the other reviewer. The full text of selected studies was analyzed if the abstract did not provide enough data to make a decision. Only studies comparing anatomic single-or double-bundle ACL reconstruction versus nonanatomic single-or double-bundle ACL reconstruction were included in this meta-analysis, regardless of graft type or fixation method. Anatomic ACL reconstruction was defined as a technique having the intra-articular opening of the femoral tunnel created by independent drilling such as the AM portal and OI techniques which may lie inside the true femoral footprint of the ACL. Non-anatomic ACL reconstruction was defined as a technique having the intra-articular opening of the femoral tunnel created by the TT technique which may lie outside the true femoral footprint of the ACL because of constraints in the direction of the tibial tunnel. Primary outcomes that were recorded included femoral tunnel length. Secondary outcomes included femoral tunnel obliquity in the coronal plane.

After eliminating duplicate results, studies were included in the meta-analysis if they (1) evaluated knees previously undergone anatomic ACL reconstruction or nonanatomic ACL reconstruction; (2) had an evidence level of 1 (high quality randomized trial or prospective study) or 2 (lesser quality randomized controlled trial or prospective comparative study) or 3 (case control study or retrospective comparative study); (3) reported a retrospective or prospective comparison of anatomic ACL reconstruction and nonanatomic ACL reconstruction cohorts; (4) included data of at least one of the following two knee joint parameters: femoral tunnel length and femoral tunnel obliquity. Femoral tunnel obliquity was calculated only in the coronal plane because insufficient detail in reporting prevented valid calculation of the effective size. Additionally, studies were included if they (5) fully reported the number of subjects in each group and the means and standard deviations for the two parameters; and (6) used adequate statistical methods to compare these parameters between groups. Conversely, studies were excluded if they (1) did not meet the inclusion criteria; if they (2) had missing or inadequate outcomes data, such as standard deviations or ranges of values; or (3) were case series, expert opinions, reviews, commentaries, or editorials.

Data extraction

Two reviewers recorded data from each study using a predefined data extraction form and resolved any differences by discussion. The data were extracted for each study: (1) author
identification; (2) year of publication; (3) study design and methodological quality information needed to complete the Cochrane Collaboration’s tool for assessing risk of bias; (4) sample size; (5) inclusion/exclusion criteria; (6) baseline characteristics; (7) surgical outcomes used such as femoral tunnel length and femoral tunnel obliquity in the coronal plane for patients with either anatomic ACL reconstruction or nonanatomic ACL reconstruction and (8) duration of follow-up.

Methodological quality assessment

Two reviewers independently assessed the methodological quality of the studies. For the Newcastle–Ottawa Scale, as recommended by the Cochrane Nonrandomized Studies Methods Working Group, we assessed studies based on the following three criteria: selection of the study groups, comparability of the groups, and ascertainment of either the exposure or the outcome of interest for case-control and cohort studies. Studies of high quality were defined as those with scores higher than six points. Two reviewers resolved all differences by discussion, and their decisions were subsequently reviewed by a third investigator.

Data synthesis and analysis

If a study presented a different surgical technique for the anatomic ACL reconstruction, data from the different surgical technique were analyzed as separate studies. If these variables were not included in the articles, the weighted mean difference was calculated from the p-value and sample size. Meta-analysis was performed using the Revman 5.3 software with a random-effects model, which was used to account for heterogeneity, and the Stata version 14.2 static software. The main outcomes of the meta-analysis were the weighted mean difference (WMD) in femoral tunnel length and femoral tunnel obliquity in the coronal plane. For all comparisons, WMD values and 95% CIs were calculated for continuous outcomes. Heterogeneity was determined by estimating the proportion of between-study inconsistencies due to actual differences between studies, rather than differences due to random error or chance. I² statistics with a value of less than 40% represents low heterogeneity and a value of 75% or more indicates high heterogeneity. When statistical heterogeneity was substantial, we conducted a meta-regression to identify potential sources of bias such as time from surgery to image and measurement tools. The risk of bias (e.g., low, high, or unclear) was independently assessed by two investigators. Publication bias was also assessed using funnel plots and Egger’s test. Subgroup analyses based on the presence or absence of human knees were performed for two endpoints to explore a potential source of heterogeneity. As a result, each group was divided into two subgroups: cadaver and noncadaver. Additionally, sensitivity analysis was performed by excluding eligible studies one at a time. Studies with data from the outside-in technique, double bundle technique, or using a flexible reamer were included, while other studies with a different study type were included. Pooling of data was feasible for the following two outcomes of interest: femoral tunnel length and femoral tunnel obliquity.

Results

Study identification, study characteristics, patient population, quality assessment, and publication bias of the included studies

Fig 1 shows details of study identification, inclusion, and exclusion. Ultimately, 27 studies were included in this meta-analysis. The 27 studies [15–38] included a total of 1,693 subjects (anatomic ACL reconstruction: 971 subjects; nonanatomic ACL reconstruction: 722 subjects). Characteristics of the included studies are described in Table 1. Quality findings of the 27
| Study | Year | Study type | Sample size (M/F) | Age | Evaluation method | Time from surgery to image | Femoral drilling technique/Graft type (SB/DB(AM)) | Cadaver or Noncadaver | Quality score | Measured parameters |
|-------|------|------------|------------------|-----|------------------|---------------------------|---------------------------------|-----------------------|-------------|-------------------|
| Hantes et al. [19] | 2009 | RCS | 30 (NA) 26 (NA) | 25.6 27.2 | MRI | 1Yr | TT (n = 30), AMP (n = 26) | Noncadaver | NOS 7 | Tunnel obliquity |
| Bediet et al. [16] | 2010 | PCS | 6 (NA) 12 (NA) | NA | CT | Immediate postoperatively | TT (n = 6), AMP (n = 12) | Cadaver | NOS 7 | Tunnel length, Tunnel obliquity |
| Bower et al. [17] | 2010 | PCS | 15 (NA) 15 (NA) | 24(16–28) 24(16–28) | MRI | 12weeks | TT (n = 15), AMP (n = 15) | Noncadaver | NOS 7 | Tunnel obliquity |
| Miller et al. [26] | 2011 | PCS | 10 (NA) 10 (NA) | 73–89 | CT | Immediate postoperatively | TT (n = 10), AMP (n = 10) | Cadaver | NOS 8 | Tunnel length |
| Chang et al. [9] | 2011 | RCS | 55 (39/16) 50 (39/11) | 31.8 ± 11.7 31.9 ± 11.7 | Intraoperative depth gauge, Plain radiograph | Immediate postoperatively | TT (n = 55), AMP (n = 50) | Noncadaver | NOS 7 | Tunnel length, Tunnel obliquity |
| Wang et al. [38] | 2012 | PCS | 20 (NA) 29 (NA0) | 32.7 ± 9 32 ± 10.8 | CT | Immediate postoperatively | TT (n = 20)/(SB), AMP (n = 20) | Noncadaver | NOS 7 | Tunnel length |
| Ilahie et al. [21] | 2012 | RCS | 35 (NA) 80 (NA) | 24.4 (14–45) 23.2 (14–46) | Intraoperative depth gauge | Immediate postoperatively | TT (n = 35), AMP (n = 80) | Noncadaver | NOS 8 | Tunnel length |
| Larson et al. [23] | 2012 | PCS | 5 (NA) 10 (NA) | 71(49–91) | CT | Immediate postoperatively | TT (n = 5), AMP (n = 10) | Cadaver | NOS 7 | Tunnel length |
| Hensler et al. [20] | 2013 | PCS | 27 (NA) 20 (NA) | NA | NA | CT | Immediate postoperatively | TT (n = 27), AMP (n = 20) | Noncadaver | NOS 7 | Tunnel length |
| Takeda et al. [34] | 2013 | PCS | 25 (19/6) 25 (19/6) | 27.6 (15–48) 27.7 (15–47) | CT | 1 week | TT (n = 25), AMP (n = 25) | Noncadaver | NOS 7 | Tunnel length, Tunnel obliquity |
| Tompkin et al. [37] | 2013 | PCS | 10 (NA) 10 (NA) | 74.9 ± 13.3 | CT | Immediate postoperatively | TT (n = 10), AMP (n = 10) | Cadaver | NOS 7 | Tunnel length |
| Pascual-Garrido et al. [1] | 2013 | RCS | 17 (NA) 23 (NA) | NA | NA | Plain radiograph | Immediate postoperatively | TT (n = 17), AMP (n = 23) | Noncadaver | NOS 7 | Tunnel length |
| Shin et al. [10] | 2014 | RCS | 37 (32/5) 82 (49/23) 46 (37/9) | 35 (19–60) 30 (15–55) 32 (16–60) | CT | Immediate postoperatively | TT (n = 37), AMP (n = 82), OI (n = 46) | Noncadaver | NOS 7 | Tunnel length |
| Lee et al. [25] | 2014 | RCS | 52 (NA) 52 (NA) | NA | NA | CT | Immediate postoperatively | TT (n = 52), AMP (n = 52) | Noncadaver | NOS 7 | Tunnel length, Tunnel obliquity |
| Song et al. [33] | 2014 | PCS | 30 (NA) 30 (NA) | NA | NA | CT | 2–6 weeks | TT (n = 30), AMP (n = 30) | Noncadaver | NOS 7 | Tunnel length |
| Seo et al. [29] | 2014 | RCS | 41 (32/9) 48 (40/8) | 30.6±11.14 32.4±13.3 | Plain radiograph | Immediate postoperatively | TT (n = 41), OI (n = 48) | Noncadaver | NOS 7 | Tunnel length |
| Sohn et al. [32] | 2014 | PCS | 20(19/1) 20(19/1) 20(17/3) | 29.5 (16–46) 26.9 (17–49) 31.4 (15–51) | Plain radiograph | Immediate postoperatively | TT (n = 20), AMP (n = 20), OI (n = 20) | Noncadaver | NOS 7 | Tunnel length, Tunnel obliquity |
| Arcuri et al. [15] | 2014 | RCS | 19 (NA) 40 (NA) | NA | NA | Plain radiograph | NA | TT (n = 19), AMP (n = 40) | Noncadaver | NOS 7 | Tunnel obliquity |
| Sirloe et al. [31] | 2014 | PCS | 20 (NA) 20 (NA) | NA | NA | CT | NA | TT (n = 20), OI (n = 20) | Noncadaver | NOS 7 | Tunnel obliquity |
| Celiktas et al. [18] | 2015 | PCS | 81 (NA) 83 (NA) | 29.6±8.4 | Plain radiograph | NA | TT (n = 81), AMP (n = 83) | Noncadaver | NOS 7 | Tunnel length, Tunnel obliquity |
| Ost et al. [28] | 2015 | PCS | 36 (20/16) 32 (27/5) 32 (19/13) | 33.59±12.17 31.2±10.64 33.74±7.32 | CT | Immediate postoperatively | TT (n = 36), AMP (n = 32), OI (n = 32) | Noncadaver | NOS 7 | Tunnel length, Tunnel obliquity |
| Tasdemir et al. [16] | 2015 | RCS | 15 (13/2) 24 (20/4) | 29.73±6.33 29.04±7.33 | MRI | 2Yrs | TT (n = 15), AMP (n = 24) | Noncadaver | NOS 6 | Tunnel obliquity |

(Continued)
| Study            | Year | Study type | Sample size (M/F) | Study type | Age | Evaluation method | Time from surgery to image | Femoral drilling technique/Graft type (SB/DB(AM)) | Cadaver or Noncadaver | Quality score | Measured parameters |
|------------------|------|------------|-------------------|------------|-----|-------------------|---------------------------|-----------------------------------------------|-----------------------|---------------|-------------------|
| Shetty et al.[30] | 2016 | RCS        | 30 (NA)           | Non-anatomical | 30 (NA) | Non-anatomical AM OI | Immediate postoperatively | TT(n = 30), AMP (n = 30) / SB | Noncadaver | NOS 7 | Tunnel obliquity |
| Jennings et al.  | 2017 | PCS        | 6 (NA)            | Non-anatomical | NA   | NA               | Intraoperatively           | TT(n = 6), AMP (n = 12) / SB | Cadaver | NOS 7 | Tunnel length |
| Nakamura et al.  | 2018 | RCS        | 20 (12/8)         | Anatomical AM | 20 (12/8) | 20 (15/5) | 26.2 ± 6.2 | Intraoperative depth gauge | Intraoperatively | TT(n = 20), AMP (n = 20) / DB | Noncadaver | NOS 8 | Tunnel length |
| Tampere et al.   | 2018 | PCS        | 10 (5/5)          | Non-anatomical | 10 (7/3) | 27(21–37) | 30.5(20–40) | CT | NA | TT(n = 10), AMP (n = 10) / SB | Noncadaver | NOS 7 | Tunnel length |
| Lee et al.[24]   | 2018 | RCS        | 50 (34/16)        | Non-anatomical | 50 (32/18) | 28.0±5.6 | 27.2±7.3 | CT | Immediate postoperatively | TT(n = 50), OI (n = 50) / SB | Noncadaver | NOS 7 | Tunnel obliquity |

Abbreviations: RCS, retrospective comparative study; PCS, prospective comparative study; M, male; F, female; NA, not available; NOS, Newcastle-Ottawa Scale; CT, computed tomography; MRI, magnetic resonance imaging; TT, transtibial; AMP, anteromedial portal; OI, outside-in; SB, Single bundle; DB, Double bundle; AM, Anteromedial

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studies included in the meta-analysis are summarized in Table 1. The non-randomized controlled trials (15 PCSs and 12 RCSs) were of high quality (Newcastle–Ottawa Scale > 6). Interrater reliabilities (k values) for all items of the Newcastle–Ottawa Scale ranged from 0.78 to 0.89, suggesting at least more than substantial agreement between the two investigators. We
evaluated the publication bias of femoral tunnel length and femoral tunnel obliquity. Funnel plots showed that the mean differences in femoral tunnel length were relatively symmetric (Fig 2A), indicating a lack of publication bias among the included studies. However, mean differences in femoral tunnel obliquity were skewed right asymmetrically, indicating some publication bias among the included studies (Fig 2B). Egger’s test confirmed these trends of publication bias in femoral tunnel length ($P = 0.297$) and femoral tunnel obliquity ($P = 0.001$), respectively.

**Femoral tunnel length**

Of the 27 studies, 21 reporting on femoral tunnel length were included. Six hundred fifty-five subjects were operated on using anatomic ACL reconstruction and 563 subjects underwent nonanatomic ACL reconstruction. The pooled data revealed that the mean difference in femoral tunnel length was 8.66 mm (95% CI: 7.10–10.22 mm; $P < 0.001$; $I^2 = 84$%; Fig 3), indicating that femoral tunnel length was significantly greater in nonanatomic ACL reconstruction than in anatomic ACL reconstruction. Six studies were assigned to the cadaver subgroup and 15 studies were assigned to the noncadaver subgroup. The cadaver subgroup demonstrated a significantly greater femoral tunnel length by 7.15 mm (95% CI: 2.69–11.61 mm; $P = 0.002$; $I^2 = 78$%; Fig 3) in nonanatomic ACL reconstruction than in anatomic ACL reconstruction. Similarly, the noncadaver subgroup showed a significantly greater femoral tunnel length by 8.66 mm (95% CI: 7.24–10.69 mm; $P < 0.001$; $I^2 = 86$%; Fig 3) in nonanatomic ACL reconstruction than in anatomic ACL reconstruction. Based on the results of sensitivity analysis, a statistical difference could not be shown as compared with the results of the original analysis, suggesting that the findings are robust in the context of decisions made in their collection process (Table 2).

**Femoral tunnel obliquity**

Of the 27 studies, 19 reporting on femoral tunnel obliquity in the coronal plane were included. Six hundred twelve subjects were operated on using anatomic ACL reconstruction and 578 subjects were operated on using nonanatomic ACL reconstruction. The pooled data showed
that the mean femoral tunnel obliquity difference was 15.29˚ (95% CI: 8.07˚–22.52˚; P < 0.001; I^2 = 99%; Fig 4), indicating that the femur tunnel obliquity of anatomic ACL reconstruction was significantly more oblique as compared with that of nonanatomic ACL reconstruction.

For subgroup analysis, two studies were assigned to the cadaver subgroup, while 17 studies were assigned to the noncadaver subgroup. In the cadaver subgroup, the anatomic ACL reconstruction led to 10.62˚ more obliquity than did nonanatomic ACL reconstruction, but this difference was not significant (95% CI: −6.12˚ to 27.37˚; P = 0.21; I^2 = 91%; Fig 4). In contrast, the pooled mean difference in the noncadaver subgroup was 15.86˚ (95% CI: 8.11˚–23.60˚; P < 0.001; I^2 = 99%; Fig 4). The results of sensitivity analysis were not significantly different from those of the original analysis, including that the findings are robust in terms of the decisions made in the process of obtaining them (Table 2).

Meta-regression analysis

The results of the meta-regression analysis are summarized in Table 3. For femoral tunnel length, between the two groups, we did not identify the time from surgery to image (P = 0.153) and measurement (P = 0.886) tool application as a source of heterogeneity. Similarly, we did not identify the time from surgery to image (P = 0.632) and measurement (P = 0.445) tool application as sources of heterogeneity for femoral tunnel obliquity between the two groups.
Discussion

The principal findings from this meta-analysis were that anatomic ACL reconstruction resulted in the femoral tunnel length and femoral tunnel obliquity being shorter and more oblique, respectively, than nonanatomic ACL reconstruction as hypothesized.

The AM portal and OI technique is able to shorten the available femoral tunnel length because of a shorter distance between the starting point and the lateral femoral cortex.\[9,10,39,40\] This shortened femoral tunnel may be associated with a lower pull-out strength and decreased graft healing as the graft has less grip on the short tunnel even though it has been investigated in other studies that 15–20 mm is plenty of pull-out strength.\[41\] For example, one study compared the length of the femoral tunnel created by either a TT or AM portal technique using 10 matched-pair fresh-frozen cadaveric knees. That study determined that shorter femoral tunnel lengths were observed when drilling through an AM portal versus using the TT technique.\[26\] These results confirm those of an earlier study, in which the length of femoral tunnel after anatomic ACL reconstruction techniques, including both the AM and OI techniques, was observed when drilling through an AM portal versus the TT technique.\[10\] In contrast, another investigation showed quite shorter tunnels than in the studies quoted previously with the TT technique, which can cause higher heterogeneous results, leading to an inconclusive meta-analysis.\[25\] This indicates that the starting position of the tibial tunnel has an impact on the femoral tunnel length, demonstrating that using a more medially located tibial tunnel between the midpoint and the posteromedial tibia allows for the creation of a shorter femoral tunnel although this may allow for a more anatomic femoral tunnel placement of the graft. However, our subgroup analysis findings that evaluated mean femoral tunnel length suggested that the femoral tunnel length was significantly greater in nonanatomic ACL reconstruction versus anatomic ACL reconstruction, regardless of the presence or absence of human knees. This discrepancy may be attributable to the fact that more oblique femoral tunnels in the coronal plane created via a far medially located tibial tunnel were less pronounced than expected. In

Table 2. Sensitivity analysis.

| Study       | Parameter       | Before exclusion | After exclusion | Statistical significance |
|-------------|-----------------|------------------|----------------|--------------------------|
| TT vs OI    | femoral tunnel  | MD = 8.66, 95%  | MD = 8.98, 95% | No difference            |
|             | length          | CI = 7.10, 10.22 | CI = 7.30,     |                          |
|             |                 | Z = 10.87, P<    | 10.66, Z = 10.49, P< 0.001 |              |
|             | femoral tunnel  | MD = 15.29, 95% | MD = 13.19, 95%| No difference            |
|             | obliquity       | CI = 8.07, 22.52 | CI = 5.71, 20.67 |                          |
|             |                 | Z = 4.15, P<     | Z = 3.46, P< 0.001 |                          |
| DB          | femoral tunnel  | MD = 8.66, 95%  | MD = 8.81, 95% | No difference            |
|             | length          | CI = 7.10, 10.22 | CI = 7.38, 11.05 |                          |
|             |                 | Z = 10.87, P<    | Z = 10.52, P< 0.001 |                          |
|             | femoral tunnel  | MD = 15.29, 95% | MD = 14.97, 95%| No difference            |
|             | obliquity       | CI = 8.07, 22.52 | CI = 7.42, 22.52 |                          |
|             |                 | Z = 4.15, P<     | Z = 3.89, P< 0.001 |                          |
| Flexible    | femoral tunnel  | MD = 8.66, 95%  | MD = 8.52, 95% | No difference            |
| reamer      | length          | CI = 7.10, 10.22 | CI = 6.89, 10.15 |                          |
|             |                 | Z = 10.87, P<    | Z = 10.24, P< 0.001 |                          |
| RCS         | femoral tunnel  | MD = 8.66, 95%  | MD = 9.11, 95% | No difference            |
|             | length          | CI = 7.10, 10.22 | CI = 6.95, 11.28 |                          |
|             |                 | Z = 10.87, P<    | Z = 8.24, P< 0.001 |                          |
|             | femoral tunnel  | MD = 15.29, 95% | MD = 15.21, 95%| No difference            |
|             | obliquity       | CI = 8.07, 22.52 | CI = 2.33, 28.09 |                          |
|             |                 | Z = 4.15, P<     | Z = 2.31, P = 0.02 |                          |

TT, transtibial; OI, outside-in; DB, double bundle; RCS, Retrospective comparative study; CI, confidence interval; MD, mean difference

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addition, research with the knee flexed to 120˚ found quite shorter tunnels than in the studies quoted previously that used the AM portal technique. These findings differ from previous reports that knee hyperflexion is required when reaming the femoral tunnel through the AM portal to avoid short tunnels.[16] This indicates that different knee flexion angles in the AM portal technique might also be potential reasons for varying results. However, this also may be different if a flexible reamer was used which can allow for a greater femoral tunnel length.

![Fig 4. Results of aggregate analysis for comparison of femoral tunnel obliquity between patients with anatomic and non-anatomic ACL reconstruction, including subgroup analysis by cadaveric and non-cadaveric studies.](https://doi.org/10.1371/journal.pone.0230497.g004)

### Table 3. Meta-regression analyses of potential sources and difference in femoral tunnel length or femoral tunnel obliquity for anatomic and non-anatomic ACL reconstruction.

| Variable                                      | Coefficient | Standard error | P value | 95% confidence interval |
|-----------------------------------------------|-------------|----------------|---------|-------------------------|
| Femoral tunnel length                         |             |                |         |                         |
| Time from surgery to image, weeks (≤12 or ≥12)| 0.998       | 0.666          | 0.153   | -0.413 to 2.410         |
| Measurement tools (CT and MRI or Others)      | -0.082      | 0.565          | 0.886   | -1.264 to 1.100         |
| Femoral tunnel obliquity                      |             |                |         |                         |
| Time from surgery to image, weeks (≤12 or ≥12)| -0.526      | 1.074          | 0.632   | -2.829 to 1.776         |
| Measurement tools (CT and MRI or Others)      | -0.675      | 0.862          | 0.445   | -2.494 to 3.459         |

CT, computed tomography; MRI, magnetic resonance imaging

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addition, research with the knee flexed to 120˚ found quite shorter tunnels than in the studies quoted previously that used the AM portal technique. These findings differ from previous reports that knee hyperflexion is required when reaming the femoral tunnel through the AM portal to avoid short tunnels.[16] This indicates that different knee flexion angles in the AM portal technique might also be potential reasons for varying results. However, this also may be different if a flexible reamer was used which can allow for a greater femoral tunnel length.

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| Femoral tunnel obliquity                      |             |                |         |                         |
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CT, computed tomography; MRI, magnetic resonance imaging

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Our findings from sensitivity analysis evaluating the use of flexible reamer for femoral tunnel length showed that the mean difference of femoral tunnel lengths are 8.66 mm (before exclusion) and 8.52 mm (after exclusion), respectively, but these differences were not significant. Furthermore, it is possible that the measured flexion angle was effectively less than 110˚ due to being covered by a tourniquet. Together, these facts clinically suggest that the accurate starting position of the tibial tunnel with the TT technique and knee hyperflexion of far greater than 120˚ with the AM portal technique may have advantages during ACL reconstruction to prevent shorter femoral tunnels.

Many studies have investigated femoral tunnel obliquity in patients who underwent conventional TT and anatomic ACL reconstruction. In biomechanical investigations, an oblique femoral tunnel position in the coronal plane improves rotatory stability as compared with a more vertical location.\[16,42\] Similarly, the current meta-analysis found that using anatomic ACL reconstruction yields a significantly more oblique femoral tunnel in comparison with the nonanatomic ACL reconstruction. However, one study acknowledged that it is possible for the surgeon to place the femoral tunnel at 60˚ in the coronal plane during nonanatomic ACL reconstruction if the surgeon maneuvers the angle of the tibial tunnel.\[25\] To obtain these better results, the entry point of the tibial tunnel must be placed more medially between the midpoint and the posteromedial point and start close to the joint line. Of 19 studies with nonanatomic ACL reconstruction, three \[16,17,19\] revealed that the angle of the femoral tunnel in the coronal plane was greater than 70˚. These different results may be caused by a less-standard starting point of the tibial tunnel, which remained compromised with nonanatomic ACL reconstruction. In contrast, of the 19 studies with anatomic ACL reconstruction, only two \[24,28\] demonstrated that the angle of the femoral tunnel in the coronal plane was less than 30˚, thus showing a much more oblique tunnel than in the studies quoted previously that used anatomic ACL reconstruction. Therefore, a considerably oblique femoral tunnel angle, which may result in more repetitive bending stress on the graft at the femoral tunnel opening, should be avoided because of increased abrasive force at the contact area on the sharp edge of the bone tunnel opening.\[7,38\]

This study had several limitations. First is that we excluded all studies concerning ACL reconstruction with clinical outcomes and only compared certain examples of anatomical ACL reconstruction such as the AM portal and OI techniques due to the nonavailability of data for assessing femoral tunnel length and femoral tunnel obliquity of anatomic or nonanatomic ACL reconstruction. However, these studies, which tended to be in larger populations, are also of importance. Therefore, this may distort the outcomes if they were put together. The second for improvement involves pooling very heterogeneous data (single and double bundle ACL reconstructions, different imaging modalities used to determine the outcomes, AM and OI techniques mixed together in the anatomic group, cadaveric versus non-cadaveric studies, and levels I, II, and III studies), which are reflected by $I^2$ values of the various analyses, although we used a random effects model, subgroup analyses, sensitivity analysis, and meta-regression analysis to incorporate heterogeneous outcomes. However, we still chose these outcomes. Therefore, this should be contemplated when one is interpreting our findings. An additional weakness is that we included one study \[22\] using a novel flexible reamer that is a significant source of heterogeneity requiring future expansion even though it could not affect the femoral tunnel length in our study.

Conclusions

Anatomic ACL reconstruction resulted in the femoral tunnel length and femoral tunnel obliquity in the coronal plane being shorter and more oblique, respectively, as compared with nonanatomic ACL reconstruction.
Supporting information

S1 Checklist. PRISMA checklist.

S1 Appendix.

Acknowledgments

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References

1. Pascual-Garrido C, Swanson BL, Swanson KE. Transtibial versus low anteromedial portal drilling for anterior cruciate ligament reconstruction: a radiographic study of femoral tunnel position. Knee Surg Sports Traumatol Arthrosc. 2013; 21:846–850. https://doi.org/10.1007/s00167-012-1988-4 PMID: 22476526
2. van Eck CF, Schreiber VM, Liu TT, Fu FH. The anatomic approach to primary, revision and augmentation anterior cruciate ligament reconstruction. Knee Surg Sports Traumatol Arthrosc. 2010; 18:1154–1163. https://doi.org/10.1007/s00167-010-1191-4 PMID: 20532865
3. Kim YK, Yoo JD, Kim SW, Park SH, Cho JH, Lim HM. Intraoperative graft isometry in anatomic single-bundle anterior cruciate ligament reconstruction. Knee Surg Relat Res. 2018; 30:115–120. https://doi.org/10.5792/kerr.16.077 PMID: 29843198
4. Kim YM, Joo YB, Lee KY, Hwang SJ. Femoral footprint for anatomical single-bundle anterior cruciate ligament reconstruction: a cadaveric study. Knee Surg Relat Res. 2018; 30:128–132. https://doi.org/10.5792/kerr.17.067 PMID: 29554719
5. Lubowitz JH. Anteromedial portal technique for the anterior cruciate ligament femoral socket: pitfalls and solutions. Arthroscopy. 2009; 25:95–101. https://doi.org/10.1016/j.arthro.2008.10.012 PMID: 19111224
6. Chhabra A, Kline AJ, Nilles KM, Harner CD. Tunnel expansion after anterior cruciate ligament reconstruction with autogenous hamstrings: a comparison of the medial portal and transtibial techniques. Arthroscopy. 2006; 22:1107–1112. https://doi.org/10.1016/j.arthro.2006.05.019 PMID: 17027409
7. Natsu-umee T, Shino K, Nakata K, Nakamura N, Toritsu Y, Mae T. Endoscopic reconstruction of the anterior cruciate ligament with quadrupled hamstring tendons. A correlation between MRI changes and
restored stability of the knee. J Bone Joint Surg Br. 2001; 83:834–837. https://doi.org/10.1302/0301-620x.83b6.11106 PMID: 11521924

8. Toritsuka Y, Shino K, Horibe S et al. Second-look arthroscopy of anterior cruciate ligament grafts with multistranded hamstring tendons. Arthroscopy. 2004; 20:287–293. https://doi.org/10.1016/j.arthro.2003.11.031 PMID: 15007317

9. Chang CB, Yoo JH, Chung BJ, Seong SC, Kim TK. Oblique femoral tunnel placement can increase risks of short femoral tunnel and cross-pin protrusion in anterior cruciate ligament reconstruction. Am J Sports Med. 2010; 38:1237–1245. https://doi.org/10.1177/036354650937608 PMID: 20348283

10. Shin YS, Ro KH, Jeon JH, Lee DH. Graft-bending angle and femoral tunnel length after single-bundle anterior cruciate ligament reconstruction: comparison of the transtibial, anteromedial portal and outside-in techniques. Bone Joint J. 2014; 96-b:743–751. https://doi.org/10.1302/0301-620X.96B6.33201 PMID: 24891573

11. Kondo E, Yasuda K. Second-look arthroscopic evaluations of anatomical double-bundle anterior cruciate ligament reconstruction: relation with postoperative knee stability. Arthroscopy. 2007; 23:1198–1209. https://doi.org/10.1016/j.arthro.2007.08.019 PMID: 17986408

12. Otsubo H, Shino K, Nakamura N, Nakata K, Nakagawa S, Koyanagi M. Arthroscopic evaluation of ACL grafts reconstructed with the anatomical two-bundle technique using hamstring tendon autograft. Knee Surg Sports Traumatol Arthrosc. 2007; 15:720–728. https://doi.org/10.1007/s00167-006-0274-8 PMID: 17235620

13. Howell SM, Gittins ME, Gottlieb JE, Traina SM, Zoellner TM. The relationship between the angle of the tibial tunnel in the coronal plane and loss of flexion and anterior laxity after anterior cruciate ligament reconstruction. Am J Sports Med.2001; 29:567–574. https://doi.org/10.1177/03635465010290050801 PMID: 11573914

14. Rupp S, Muller B, Seil R. Knee laxity after ACL reconstruction with a BPTB graft. Knee Surg Sports Traumatol Arthrosc. 2001; 9:72–76. https://doi.org/10.1007/s001670010177 PMID: 11354856

15. Arcuri F, Barclay F, Nacul I. Anterior cruciate ligament reconstruction: Transtibial vs transportal radiographic evaluation on femoral and tibial tunnel position. Orthop J Sports Med. 2014; 2.

16. Bedi A, Raphael B, Maderazo A, Pavlov H, Williams RJ 3rd. Transtibial versus anteromedial portal drilling for anterior cruciate ligament reconstruction: a cadaveric study of femoral tunnel length and obliquity. Arthroscopy. 2010; 26:342–350. https://doi.org/10.1016/j.arthro.2009.12.006 PMID: 20206044

17. Bowers AL, Bedi A, Lipman JD et al. Comparison of anterior cruciate ligament position and graft obliquity with transtibial and anteromedial portal femoral tunnel reaming techniques using high-resolution magnetic resonance imaging. Arthroscopy. 2011; 27:1511–1522. https://doi.org/10.1016/j.arthro.2011.07.007 PMID: 21963097

18. Celiktas M, Kose O, Sarpel Y, Gulsen M. Can we use intraoperative femoral tunnel length measurement as a clue for proper femoral tunnel placement on coronal plane during ACL reconstruction? Arch Orthop Trauma Surg. 2015; 135:523–528. https://doi.org/10.1007/s001670000177 PMID: 25701457

19. Hantes ME, Zachos VC, Liantsis A, Venouzou A, Karantanas AH, Malizos KN. Differences in graft orientation using the transtibial and anteromedial portal technique in anterior cruciate ligament reconstruction: a magnetic resonance imaging study. Knee Surg Sports Traumatol Arthrosc. 2009; 17:880–886. https://doi.org/10.1007/s00167-009-0738-8 PMID: 19238359

20. Hensler D, Working ZM, Illingworth KD, Tashman S, Fu FH. Correlation between femoral tunnel length and tunnel position in ACL reconstruction. J Bone Joint Surg Am. 2013; 95:2029–2034. https://doi.org/10.2106/JBJS.L.01315 PMID: 24257661

21. Iliahi OA, Ventura NJ, Qadeer AA. Femoral tunnel length: accessory anteromedial portal drilling versus transtibial drilling. Arthroscopy. 2012; 28:486–491. https://doi.org/10.1016/j.arthro.2011.09.018 PMID: 22264829

22. Jennings JK, Leas DP, Fleischli JE, D’Alessandro DF, Peindl RD, Piasecki DP. Transtibial Versus Anteromedial Portal ACL Reconstruction: Is a Hybrid Approach the Best? Orthop J Sports Med. 2017; 5:23259671. https://doi.org/10.1016/j.arthro.2016.07.007 PMID: 2675661

23. Larson AI, Bullock DP, Pevny T. Comparison of 4 femoral tunnel drilling techniques in anterior cruciate ligament reconstruction. Arthroscopy. 2012; 28:972–979. https://doi.org/10.1016/j.arthro.2011.12.015 PMID: 22408948

24. Lee DW, Kim JG, Lee JH, Park JH, Kim DH. Comparison of Modified Transtibial and Outside-In Techniques in Anatomic Single-Bundle Anterior Cruciate Ligament Reconstruction. Arthroscopy. 2018; 34:2857–2870. https://doi.org/10.1016/j.arthro.2018.05.041 PMID: 29197202

25. Lee JK, Lee S, Seong SC, Lee MC. Anatomic single-bundle ACL reconstruction is possible with use of the modified transtibial technique: a comparison with the anteromedial transportal technique. J Bone Joint Surg Am. 2014; 96:664–672. https://doi.org/10.2106/JBJS.M.00088 PMID: 24740663
26. Miller CD, Gerdeman AC, Hart JM et al. A comparison of 2 drilling techniques on the femoral tunnel for anterior cruciate ligament reconstruction. Arthroscopy. 2011; 27:372–379. https://doi.org/10.1016/j.arthro.2010.08.012 PMID: 21109387

27. Nakamura T, Koga H, Otabe K et al. Comparison of three approaches for femoral tunnel during double-bundle anterior cruciate ligament reconstruction: A case controlled study. J Orthop Sci. 2019; 24:147–152. https://doi.org/10.1016/j.jos.2018.08.014 PMID: 30245095

28. Osti M, Krawinkel A, Ostermann M, Hoffelner T, Benedetto KP. Femoral and tibial graft tunnel parameters after transtibial, anteromedial portal, and outside-in single-bundle anterior cruciate ligament reconstruction. Am J Sports Med. 2015; 43:2250–2258. https://doi.org/10.1177/0363546515590221 PMID: 26138734

29. Seo SS, Kim CW, Kim JG, Jin SY. Clinical results comparing transtibial technique and outside in technique in single bundle anterior cruciate ligament reconstruction. Knee Surg Relat Res. 2013; 25:133–140. https://doi.org/10.5792/kssr.2013.25.3.133 PMID: 24032102

30. Shetty SM, Shetty V, Ballal A, Mohanchandran J, Hegde A. A radiological comparative study between transtibial & anteromedial portal drilling of femoral tunnel in single bundle anterior cruciate ligament reconstruction: A comparison of four angles. Arthroscopy. 2016; 3:22–27.

31. Sirleo L, Matassi F, Carulli C, Soderi S, Piacentini F, Innocenti M. Anatomic anterior cruciate ligament reconstruction: Transtibial technique (TT) versus translateral technique (OUT-IN). J Orthop and Traumatol. 2014; 15:S50.

32. Sohn OJ, Lee DC, Park KH, Ahn HS. Comparison of the modified transtibial technique, anteromedial portal technique and outside-in technique in ACL reconstruction. Knee Surg Relat Res. 2014; 26:241–248. https://doi.org/10.5792/kssr.2014.26.4.241 PMID: 25505707

33. Song EK, Lim HA, Seon JK. Comparisons of tunnel-graft angle and tunnel length and position between transtibial and transportal techniques in anterior cruciate ligament reconstruction. Int Orthop. 2014; 38:2357–2362. https://doi.org/10.1007/s00267-014-2457-0 PMID: 25120231

34. Takeda Y, Iwame T, Takasago T et al. Comparison of tunnel orientation between transtibial and anteromedial portal techniques for anatomic double-bundle anterior cruciate ligament reconstruction using 3-dimensional computed tomography. Arthroscopy. 2013; 29:195–204. https://doi.org/10.1016/j.arthro.2012.08.020 PMID: 23270788

35. Tampere T, Devriendt W, Cromheecke M, Luyckx T, Verstraete M, Victor J. Tunnel placement in ACL reconstruction surgery: smaller inter-tunnel angles and higher peak forces at the femoral tunnel using anteromedial portal femoral drilling-a 3D and finite element analysis. Knee Surg Sports Traumatol Arthrosc. 2018.

36. Tasdemir Z, Gulabi D, Saglam F, Tokgoz Ozal S, Elmali N. Does the anteromedial portal provide clinical superiority compared to the transtibial portal in anterior cruciate ligament reconstruction in nonprofessional athletes in short-term follow-up? Acta Orthop Traumatol Turc. 2016; 48:483–491. https://doi.org/10.3944/AOTT.2015.15.0016 PMID: 26422342

37. Tompkins M, Cosgrove CT, Millewski MD, Brockmeier SF, Hart JM, Miller MD. Anterior cruciate ligament reconstruction femoral tunnel characteristics using an accessory medial portal versus traditional transtibial drilling. Arthroscopy. 2013; 29:550–555. https://doi.org/10.1016/j.arthro.2012.10.030 PMID: 23544689

38. Wang JH, Kim JG, Lee DK, Lim HC, Ahn JH. Comparison of femoral graft bending angle and tunnel length between transtibial technique and transportal technique in anterior cruciate ligament reconstruction. Knee Surg Sports Traumatol Arthrosc. 2012; 20:1584–1593. https://doi.org/10.1007/s00167-011-1781-9 PMID: 22120838

39. Golish SR, Baumfeld JA, Schoderbek RJ, Miller MD. The effect of femoral tunnel starting position on tunnel length in anterior cruciate ligament reconstruction: a cadaveric study. Arthroscopy. 2007; 23:1187–1192. https://doi.org/10.1016/j.arthro.2007.06.013 PMID: 17986406

40. Nakamura M, Deie M, Shibuya H et al. Potential risks of femoral tunnel drilling through the far anteromedial portal: a cadaveric study. Arthroscopy. 2009; 25:481–487. https://doi.org/10.1016/j.arthro.2008.11.010 PMID: 19409305

41. Greis PE, Burks RT, Bachus K, Luker MG. The influence of tendon length and fit on the strength of a tendon-bone tunnel complex. A biomechanical and histologic study in the dog. Am J Sports Med. 2001; 29:493–497. https://doi.org/10.1177/03635465010290041901 PMID: 11476392

42. Scopp JM, Jasper LE, Belkoff SM, Moorman CT 3rd. The effect of oblique femoral tunnel placement on rotational constraint of the knee reconstructed using patellar tendon autografts. Arthroscopy, 2004; 20:294–299. https://doi.org/10.1016/j.arthro.2004.01.001 PMID: 15007318