


# Comparative Meta-Analysis of ACL Footprint Anatomy Between Asian and Western Populations

Chen Wang,\* MD, PhD, Ying Ren Mok,\* MBBS, MMed (Ortho), MSpMed (Aus), Ming Wang,\* MD, MMed (Ortho), Xin Ma,<sup>†</sup> MD, PhD, James Hoi Po Hui,\* MBBS, and Dave Yee Han Lee,\*<sup>‡</sup> MBBS, MMed (Ortho) 

*Investigation performed at the National University Hospital, Singapore*

**Background:** The success of anterior cruciate ligament (ACL) reconstruction is influenced by precise anatomic knowledge, which may vary across populations. Despite extensive research on ACL anatomy, direct comparisons between Asian and Western populations remain unexplored.

**Purpose/Hypothesis:** The purpose of this study is to systematically compare the footprint size and location of ACL and its individual bundles in Asian and Western populations. It was hypothesized that the ACL footprint size and location of the Asian population would differ from those in the Western population.

**Study Design:** Systematic review; Level of evidence, 4.

**Methods:** A systematic review and single-arm meta-analysis were conducted in accordance with the PRISMA (Preferred Reporting Items for Systematic Reviews and Meta-Analyses) guidelines. Studies on ACL footprint anatomy were included and stratified into subgroups based on the origin of the data (Asian or Western regions). Meta-analyses were performed for femoral and tibial footprint locations of the entire ACL and its anteromedial and posterolateral bundles. The ACL femoral and tibial footprint areas were also compared. Statistical heterogeneity was assessed using a random-effects model.

**Results:** A total of 50 studies with 1652 knees were included in the meta-analysis, with 25 studies per subgroup. The center of the ACL femoral footprint was located at 35.2% and 27.3% from the posterior edge of the lateral femoral condyle in the Asian and Western subgroups, respectively ( $P < .001$ ), and 39.4% and 33% from the Blumensaat line, respectively ( $P = .049$ ). The Asian subgroup exhibited smaller femoral footprint areas (96.3 mm<sup>2</sup> [95% CI, 81.1-111.4] vs 126.8 mm<sup>2</sup> [95% CI, 103.5-150];  $P = .03$ ). No significant difference was found in the tibial footprint location or size.

**Conclusion:** This meta-analysis demonstrated that the ACL femoral footprint in the Asian population is located more anteriorly and distally than in the Western population, and the femoral footprint size is smaller. These findings provide valuable insights for population-specific surgical strategies in the future.

**Keywords:** anatomy; anterior cruciate ligament; anterior cruciate ligament reconstruction; footprint; ethnic variations

Significant interest continues to be shown in exploring the anatomy of the anterior cruciate ligament (ACL) in the 21st century because of its complex structure.<sup>4,12,25,47,50,58,78,82</sup> According to Morales-Avalos et al,<sup>55</sup> >2700 articles on ACL anatomy and approximately 14900 articles covering ACL-related topics have been published in the past decade. It is suggested that precise anatomic ACL reconstructions (ACLR) could achieve

significantly better joint stability and knee joint functionality.<sup>8,17,34,70</sup>

Previous studies have highlighted differences in knee ligamentous anatomy between Asian and Western populations.<sup>21,42</sup> A recent systematic review of the knee anterolateral ligament<sup>21</sup> revealed its presence in 82% of North Americans, 65% of Europeans, and only 46% of Asians. Previous systematic reviews on ACL anatomy have reported high variability among included anatomic studies. However, no study has yet compared ACL anatomy among different ethnic groups.

The Orthopaedic Journal of Sports Medicine, 13(12), 23259671251397407

DOI: 10.1177/23259671251397407

© The Author(s) 2025

This open-access article is published and distributed under the Creative Commons Attribution - NonCommercial - No Derivatives License (<https://creativecommons.org/licenses/by-nc-nd/4.0/>), which permits the noncommercial use, distribution, and reproduction of the article in any medium, provided the original author and source are credited. You may not alter, transform, or build upon this article without the permission of the Author(s). For article reuse guidelines, please visit SAGE's website at <http://www.sagepub.com/journals-permissions>.

Furthermore, the emergence of novel anatomic measurement techniques, such as 3-dimensional (3D) magnetic resonance imaging (MRI) reconstruction<sup>74,81,82</sup> and 3D histological reconstruction,<sup>32,69</sup> has led to new findings and data—including the precise footprint locations of the anteromedial band and posterolateral bundles of the ACL or the extensive femoral insertion of the ACL's fan-like fibers.

The present study aimed to systematically compare the ACL footprint size and location between Asian and Western populations using a meta-analysis that strictly includes comparable, quantitative, and updated anatomic data. This study aimed to provide a practical understanding of the differences in ACL footprint and inform population-specific surgical strategies.

## METHODS

### Data Sources and Search Strategy

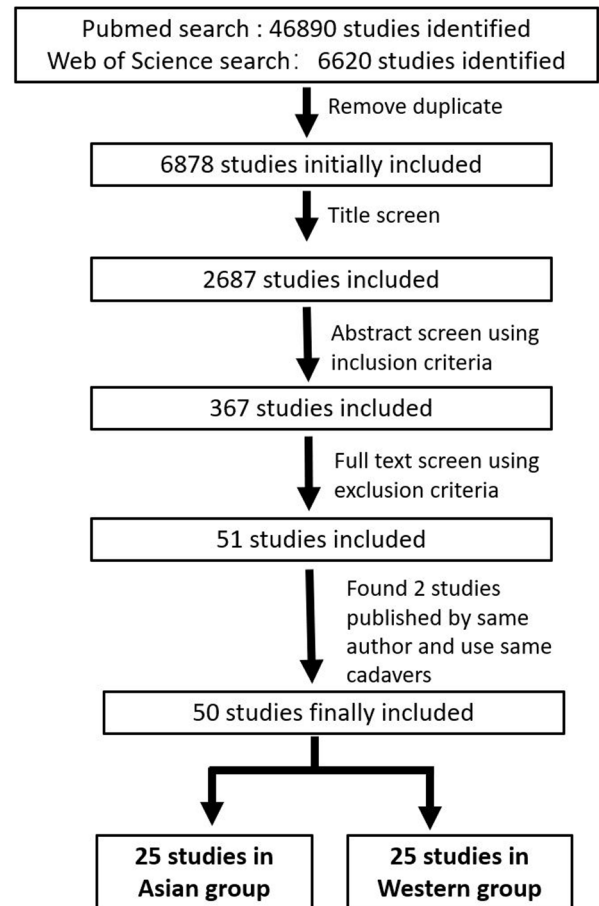
This study was conducted by following the PRISMA (Preferred Reporting Items for Systematic Reviews and Meta-Analyses) 2020 guideline. A search of the Web of Science and PubMed databases was performed in July 2024. Search strategy for Pubmed database was (("Anterior Cruciate Ligament"[Mesh] OR "ACL" OR "cruciate ligament") AND ("Anatomy"[Mesh] OR "morphometry" OR "morphology" OR "size" OR "dimensions" OR "structure" OR "footprint" OR "location")) NOT ("Child"[Mesh] or "Children" or "pediatric" or "paediatric").

The search strategy for Web of Science database was TS = ("Anterior Cruciate Ligament" OR "ACL" OR "cruciate ligament") AND ("anatomy" OR "morphometry" OR "morphology" OR "size" OR "dimensions" OR "structure" OR "footprint" OR "location")) NOT TS = ("child\*" OR "children" OR "pediatric\*" OR "paediatric\*") AND PY = (1994-2024).

### Inclusion and Exclusion Criteria

The criteria for inclusion were met if studies (1) were published from Asia, North America, or Europe; (2) studies published in English or abstract in English, which included all necessary data; (3) studies on human adults; and (4) studies that measured the anatomy of ACL femoral or tibial footprints through cadaveric dissection, radiological images, histologic analysis, or arthroscopic measurements.

To conduct a meta-analysis between Asian and Western groups, studies were excluded based on the following criteria: (1) studies containing only descriptive anatomic



**Figure 1.** Flowchart of study screening based on the inclusion and exclusion criteria.

results without precise data measurement of the ACL femoral or tibial footprint; (2) case reports, editorials, reviews, letters, and other nonoriginal research papers; (3) studies where cadaveric specimens or patients were not consistent with their publication region; (4) studies measuring intraoperative femoral or tibial tunnel sizes or locations instead of natural ACL footprints; (5) For femoral and tibial footprint location studies, those not using the standard quadrant method were excluded; (6) Studies that did not report the footprint size area in either mm<sup>2</sup> or cm<sup>2</sup> were excluded; and (7) For studies published by the same author using the identical cadaveric specimens, only 1 study was included to avoid duplication.

The inclusion and exclusion flowchart following the PRISMA guidelines is shown in Figure 1.

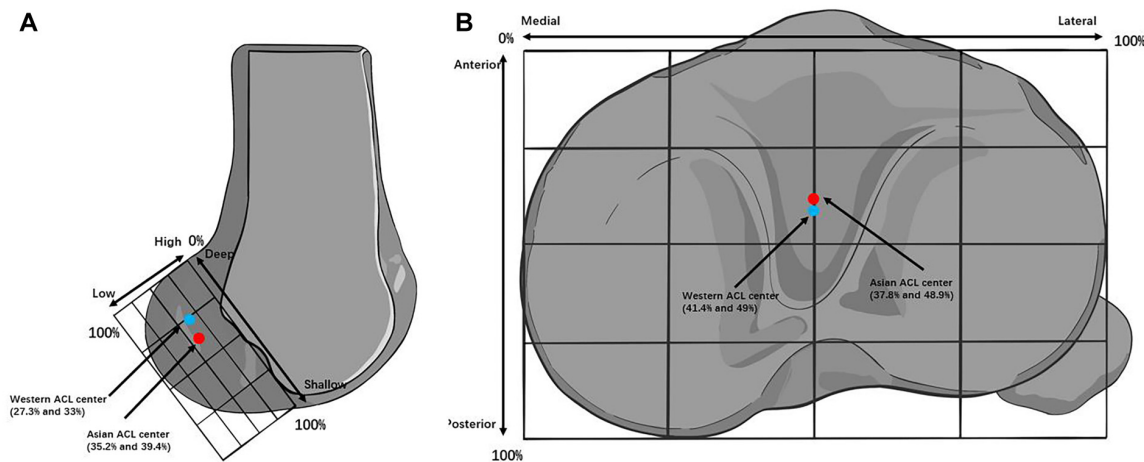
‡Address correspondence to Dave Yee Han Lee, MBBS, MMed (Ortho), Department of Orthopedic Surgery, National University Hospital, 1 East Kent Ridge Road, Singapore, Singapore, 119228 (email: daveyh@singnet.com.sg).

\*National University Hospital, Singapore.

†Shanghai Sixth People's Hospital, Shanghai, China.

Final revision submitted August 24, 2025; accepted September 24, 2025.

The authors have declared that there are no conflicts of interest in the authorship and publication of this contribution. AOSSM checks author disclosures against the Open Payments Database (OPD). AOSSM has not conducted an independent investigation on the OPD and disclaims any liability or responsibility relating thereto.



**Figure 2.** (A) Quadrant measurement method on the lateral femoral condyle. The red dot represents the mean location of the ACL footprint center in the Asian group, and the blue dot represents the mean location in the Western group. ACL, anterior cruciate ligament. (B) Quadrant measurement method on the tibial plateau. The red dot represents the mean location of the ACL footprint center in the Asian group, and the blue dot represents the mean location in the Western group. ACL, anterior cruciate ligament.

## Data Extraction and Outcomes

Data extraction focused on (1) basic information—including author, publication year, and region; (2) study materials—including sex, mean age of cadaveric specimens, or adult patients; (3) methods for measuring ACL footprint—including cadaveric dissection, radiograph-based measurement, MRI reconstruction, computed tomography (CT) reconstruction, or histologic reconstruction; and (4) anatomic measurement data—including femoral footprint location, tibial footprint location, and footprint size (in  $\text{mm}^2$  or  $\text{cm}^2$ ).

## Femoral Footprint Location

The femoral footprint of the native ACL was measured using various methods. To reduce heterogeneity among the included studies and minimize statistical bias, only studies that used the quadrant method were included. Such a method was first described by Bernard et al<sup>2</sup> in 1997 and has been the most frequently used method.

The quadrant measurement was conducted on a true lateral radiography of the knee with superimposed medial and lateral condyles or on a standard photograph of the medial side of the lateral condyle (Figure 2). A grid was drawn to fit the distal lateral femoral condyle, with its upper border aligned to the Blumensaat line, and other borders tangential to the cartilage surface of the lateral femoral condyle on the anterior, bottom, and medial sides. The locations of the ACL center or the anteromedial (AMB)/posterolateral (PLB) bundle were expressed as a percentage within the grid (Figure 2A).

## Tibial Footprint Location

The quadrant method for tibial footprint location was conducted using an axial view of the tibial plateau photograph

or a 3D CT reconstruction image. A grid was aligned with the tibial plateau, with borders tangential to the anterior, medial, and posterior edges of the medial tibial plateau and the lateral border of the lateral tibial plateau. The location of the ACL center or the AMB/PLB bundle was expressed as a percentage within the grid (Figure 2B).

## Subgroup Allocation

Final included studies were allocated to the Asian group if both the publication region and the cadaveric specimens/patients originated in Asia. Studies were assigned to the Western group if both the publication region and cadaveric specimens/patients originated from Europe or North America.

## Risk of Bias and Quality Assessment

To evaluate bias and quality in this single-arm meta-analysis, we adopted a risk-of-bias assessment approach based on a method specifically designed for single-arm studies.<sup>22</sup> Article quality was assessed using the Newcastle-Ottawa Scale, with a focus on the reliability of outcome measurements.<sup>61</sup> A detailed summary of the bias evaluation and quality grading of the included studies is provided in the supplementary 5.

## Statistical Analysis

Baseline characteristics comparisons between subgroups were performed in SPSS Statistics, Version 23.0 (IBM). The mean age was compared using a 1-sample *t* test. Non-continuous data—including sex distribution and the number of knees investigated by radiographic method—were compared using the chi-squared test.

TABLE 1  
Basic Characteristics of Included Studies in Both Subgroups<sup>a</sup>

	Asian Group	Western Group	Total/P Value
Total number of studies	25	25	50
Total number of knees	704	948	1652
Publication countries	Japan (n = 19) Republic of Korea (n = 3) China (n = 3)	USA (n = 11) Germany (n = 4), Netherlands (n = 1), Australia (n = 1) Spain (n = 1), Switzerland (n = 1), France (n = 2), Canada (n = 1), Belgium (n = 1), UK (n = 2)	
Sex, numbers reported in studies	349 men                      300 women	254 men                      194 women	.339
Mean age, years	71.3 ± 17.5	61.8 ± 18.5	.07
Publication year, number of knees in studies of the last 10 years	483 knees, studies after 2014 221 knees, studies before 2013	579 knees, studies after 2014 369 knees, studies before 2013	<b>.002</b>
Study methods, number of knees investigated by radiography or by dissection with photo	279 knees, by radiography 425 knees, by dissection and photo	413 knees, radiography 535 knees, dissection, and photo	.11

<sup>a</sup>Data are provided as the mean ± SD, unless otherwise indicated. The *P* value indicates a significant difference.

A single-arm meta-analysis was performed using RStudio Version 2024.09.01 (Posit PBC) for all extracted continuous data—including femoral or tibial footprint locations and areas.

To conduct the single-arm meta-analysis, the *meta* package was first installed in RStudio. The *metamean* function was then executed using mean values, sample sizes, and standard deviations. A random-effect model was applied to account for variations between studies. Weighted means were calculated using the inverse variance method, and the heterogeneity parameter was estimated using restricted maximum likelihood.

After the analysis, the overall effect size results provided the mean estimate and 95% CI. Subgroup analyses presented the mean estimates and heterogeneity metrics for each group, with subgroup differences assessed using the *Q*-test.

The threshold for statistical significance was set at *P* < .05. When standard deviation data were not provided in the original article, they were calculated based on similar studies.

Heterogeneity within subgroups and between the 2 subgroups was evaluated using the *I*<sup>2</sup> value. Heterogeneity was classified as minimal, moderate, and significant when *I*<sup>2</sup> values were between 0% and 30%, 30% and 60%, or >60%, respectively.<sup>61</sup>

## RESULTS

A total of 50 studies, involving 1652 knees, were included in this study. Among these, 25 studies were assigned to the Asian group, with 704 knees.<sup>§</sup> The remaining 25 studies were allocated to the Western group, with 948 knees.<sup>||</sup> Basic characteristics of the 2 groups are shown in Table 1. A total

of 649 knees in the Asian group and 448 knees in the Western group had reported sex distributions, with male-to-female ratios of 1.16 and 1.3, respectively. No significant differences were observed in terms of sex distribution, mean age, or study methods. However, a significant difference was observed in publication years, with a higher percentage of knees in studies published within the past 10 years in the Asian group than in the Western group (65% vs 61%).

The results of the single meta-analysis are summarized in Table 2.

The mean location of the ACL footprint center in the Asian group and the Western group was demonstrated in Figure 2.

## Footprint Locations

For femoral footprint locations of the whole ACL (Figure 3 with detailed data in supplementary 1) in the shallow-deep direction, the mean femoral footprint center was located at 35.2% and 27.3% from the posterior edge of the lateral condyle in Asian and Western groups, respectively (*P* < .001). In the high-low direction, the center was located at 39.4% and 33% from the Blumensaat line, respectively (*P* = .049).

For the tibial footprint locations of the entire ACL (Figure 4 with detailed data in supplementary 2), no significant differences were observed between Asian and Western groups in the anteroposterior direction (*P* = .26) and mediolateral direction (*P* = .95).

For the AMB and PLB bundles (Supplementary Figures 6 and 7), (1) a significant difference was observed in the femoral shallow-deep direction (*P* = .004 and *P* = .005, respectively); and (2) no significant differences were found in the femoral high-low direction or the tibial anteroposterior and mediolateral directions.

## Footprint Size

For the femoral footprint size (Figure 5A; detailed data in Supplementary 3), 17 studies from the Asian group (479 knees) and 12 studies from the Western group (585 knees)

<sup>§</sup>References 11, 18, 24-30, 32, 33, 36, 38-40, 43, 50, 56, 57, 76, 77, 79, 83, 84, 86.

<sup>||</sup>References 1, 2, 5-7, 10, 13-16, 20, 35, 45, 46, 49, 54, 58, 63, 65, 73, 74, 80, 82, 87, 88.

TABLE 2  
Summary of Single-Arm Meta-analysis Results<sup>a</sup>

		Asian Countries		Western Countries		P
		Total Number of Knees for Comparison	Mean, %	Total Number of Knees for Comparison	Mean, %	
ACL femoral footprint center	SD direction	176	35.2 [31.2-39.2]	209	27.3 [25.3-29.3]	<.001
	HL direction	176	39.4 [34.5-44.3]	209	33 [28.9-37.1]	.049
ACL tibial footprint center	AP direction	133	37.8 [32.1-43.5]	166	41.4 [38.5-44.4]	.26
	ML direction	83	48.9 [48-49.9]	115	49 [46.7-51.4]	.95
AMB femoral footprint center	SD direction	83	30.3 [25.7-25.2]	183	22.7 [20.6-24.8]	.004
	HL direction	83	23.3 [17.5-29]	183	22.4 [17.3-26.6]	.73
PLB femoral footprint center	SD direction	83	38.3 [34.6-41.9]	183	31.4 [28.4-34.4]	.005
	HL direction	83	50.5 [41.9-59]	183	50 [46.5-53.6]	.93
AMB tibial footprint center	AP direction	133	34.5 [30.4-38.7]	158	33.1 [29.1-37.1]	.63
	ML direction	83	45.9 [44-47.9]	115	37.5 [44.8-48.4]	.47
PLB tibial footprint center	AP direction	133	41 [33.5-48.5]	158	48.4 [46-50.8]	.06
	ML direction	83	52.1 [51.2-53]	115	50.4 [48.3-52.4]	.13
ACL femoral footprint size		479	96.255 [81.1-111.4]	585	126.8 [103.5-150]	.03
ACL tibial footprint size		301	125.2 [115.2-135.2]	556	136.4 [123-149.7]	.10

<sup>a</sup>Data are presented as mean % [95 CI %]. Bold P values indicate statistical significance. ACL, anterior cruciate ligament; AMB, antero-medial; AP, anteroposterior; HL, high-low; ML, mediolateral; PLB, posterolateral; SD, shallow-deep.

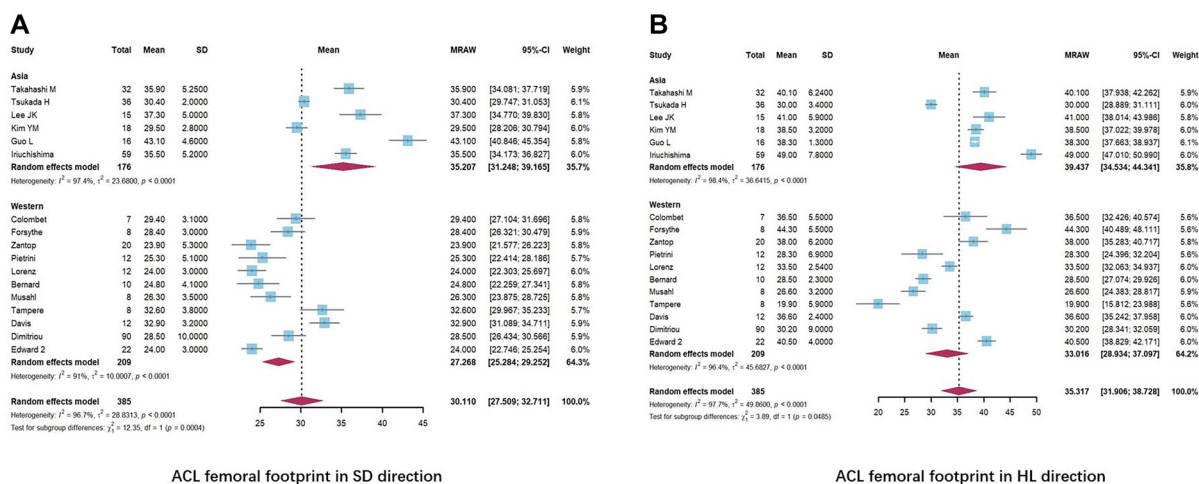


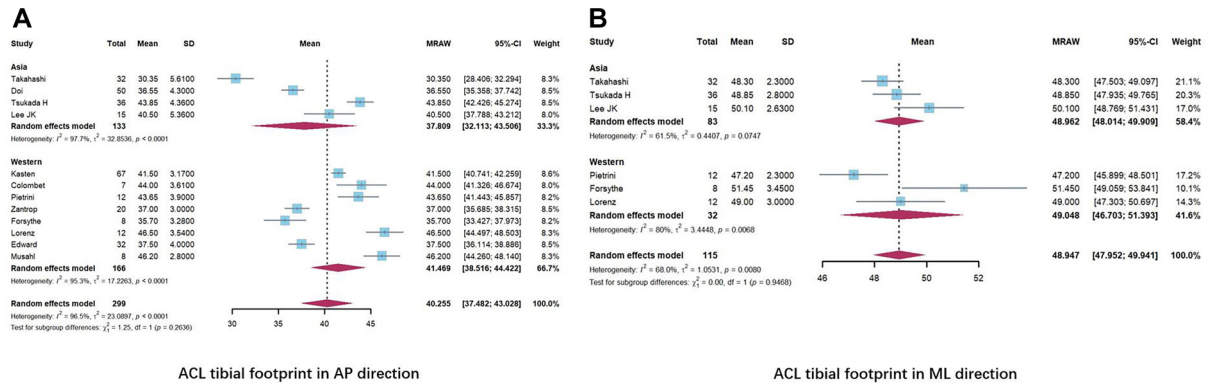
Figure 3. (A) Forest plot of single-arm meta-analysis results for the ACL femoral footprint center location in the SD direction. (B) Forest plot of single-arm meta-analysis results for the ACL femoral footprint center location in the HL direction. ACL, anterior cruciate ligament; HL, high-low; SD, shallow-deep.

were included. The mean area of the ACL femoral footprint was 96.3 mm<sup>2</sup> [95% CI, 81.1-111.4] in the Asian group and 126.8 mm<sup>2</sup> [95% CI, 103.5-150] in the Western group (P = .03).

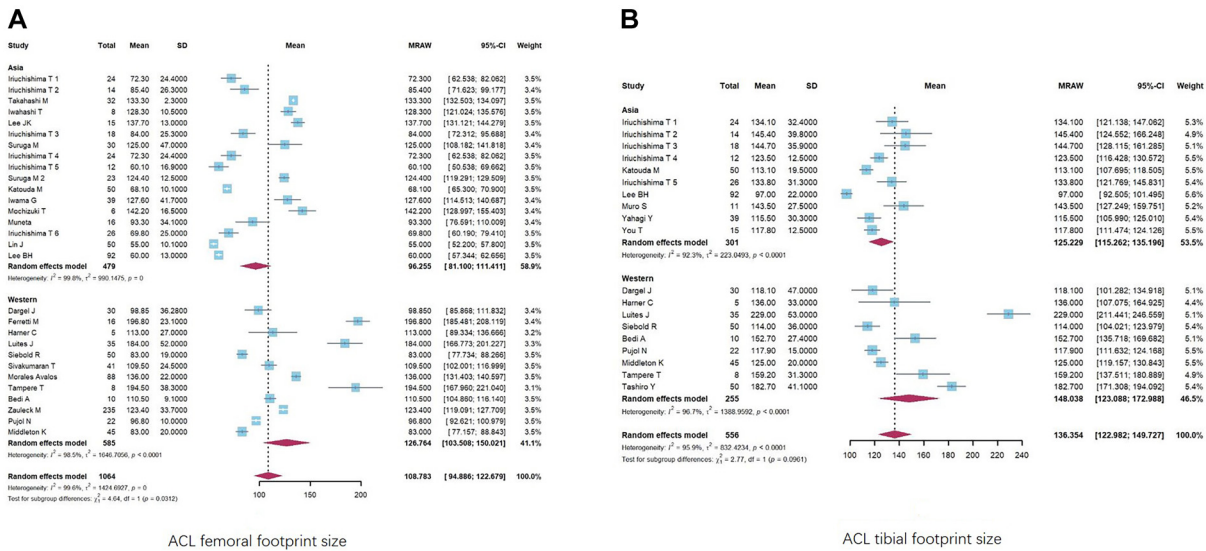
For the tibial footprint size, 10 studies from the Asian group (301 knees) and 9 studies from the Western group (255 knees) were included (Figure 5B and Supplementary 4). The mean area of the ACL tibial footprint was 125.2 mm<sup>2</sup> [95% CI, 115.3-135.2] in Asian and 148 mm<sup>2</sup> [95% CI, 123.1-173] in Western groups (P = .09).

DISCUSSION

The most significant findings of our study were that substantial differences in the ACL footprint anatomy between Asian and Western groups were primarily observed on the femoral side—including the location and size of the femoral footprint. Using the quadrant method on the distal femoral lateral condyle, the center of the ACL footprint was located at 32.5% in the Asian group and 27.3% in the Western



**Figure 4.** (A) Forest plot of single-arm meta-analysis results for the ACL tibial footprint center location in the AP direction. (B) Forest plot of single-arm meta-analysis results for the ACL tibial footprint center location in the ML direction. ACL, anterior cruciate ligament; AP, anteroposterior; ML, mediolateral.



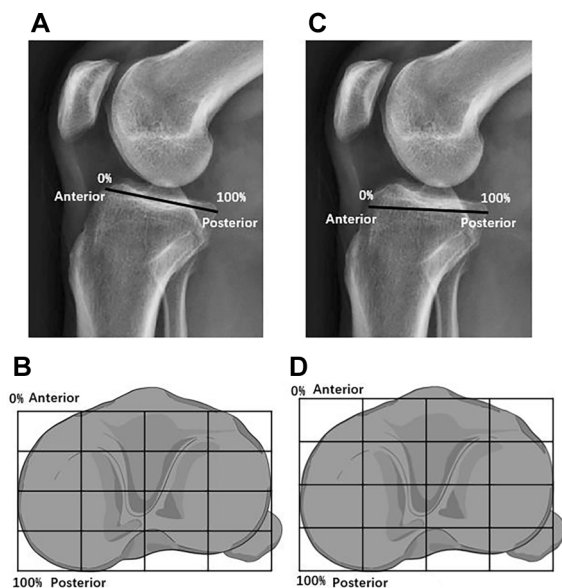
**Figure 5.** (A) Forest plot of single-arm meta-analysis results for ACL femoral footprint size. (B) Forest plot of single-arm meta-analysis results for ACL tibial footprint size. ACL, anterior cruciate ligament.

group from the posterior edge of the lateral condyle. Meanwhile, from the upper border, which corresponds to the Blumensaat line, the distances were 39.4% and 33% in the Asian and the Western groups, respectively.

To our knowledge, this is the first meta-analysis to systematically compare all eligible data from Asian and Western studies regarding ACL footprint anatomy. These results indicate that the ACL femoral insertion in the Asian population is located significantly shallower than in the Western group. To facilitate an understanding of the exact difference regarding ACL femoral footprint locations in clinical practice, our findings can also be interpreted to suggest that the ACL femoral footprint in the Asian population is more anteriorly and distally located.

We also found that the total ACL femoral footprint area was significantly smaller in the Asia population.

With the advancement of ACLR techniques, additional surgical considerations arise during surgery—including graft choices and fixation methods.<sup>48,64,70</sup> However, placing the femoral and tibial graft tunnels as close as possible to the native ACL insertion, along with appropriate graft size selection, remains crucial for postoperative knee joint stability and functional recovery.<sup>68,71</sup> Our study greatly enhances the understanding of ACL footprint anatomy, particularly highlighting an important aspect that may have been overlooked: the significant differences between ethnic groups, which should be considered when performing reconstruction surgeries for patients of different ethnic groups.



**Figure 6.** Comparison of 2 methods for defining the tibial anterior ridge. (A and B) The Amis and Jakob method, which defines the tibial anterior ridge as the most anterior point of the cartilage surface, with the line parallel to the tibial plateau. (C and D) The Staubli method, which defines the tibial anterior ridge as the most anterior point of the bony ridge, with the line horizontal.

Recent ACL anatomy studies<sup>40,51,77,79,83</sup> have widely accepted the concept that the ACL ligament is primarily composed of 2 bundles: the AMB and PLB. Therefore, more anatomical data regarding the AMB and PLB bundles have been reported, particularly in the past 10 years. As the most up-to-date data were included in our study, we were able to analyze the footprint locations of both AMB and PLB bundles. Our results revealed that the femoral centers for both bundles were located significantly shallower in the Asia group, consistent with our main finding regarding the ACL femoral footprint location, and further supporting the differences between subgroups.

The ideal location for the femoral tunnel in anatomic ACLR remains controversial. Some recent studies from Aisa<sup>18,40,43</sup> have found that the outcomes of ACL femoral footprint location tend to be shallower than reported in earlier data. Lee et al<sup>40</sup> suggested that this discrepancy could be due to the technical evolution of measurement methods in the 21st century. As a result, some previous systematic reviews intentionally excluded studies before 2000. However, as we observed, several studies<sup>2,20,56</sup> published before the 21<sup>st</sup> century, which were included in the current study, used reasonable cadaveric resources and the same quadrant measurement method. Intentionally excluding these studies could introduce potential selection bias.

A recent 3D-MRI reconstruction study from Asia also reported femoral footprint locations that were 25% and 45% and 23.8% and 37.3% in the deep-shallow direction and 41% and 48% and 26.6% and 44.3% in the high-low direction, for Asian and Western groups, respectively.<sup>43</sup>

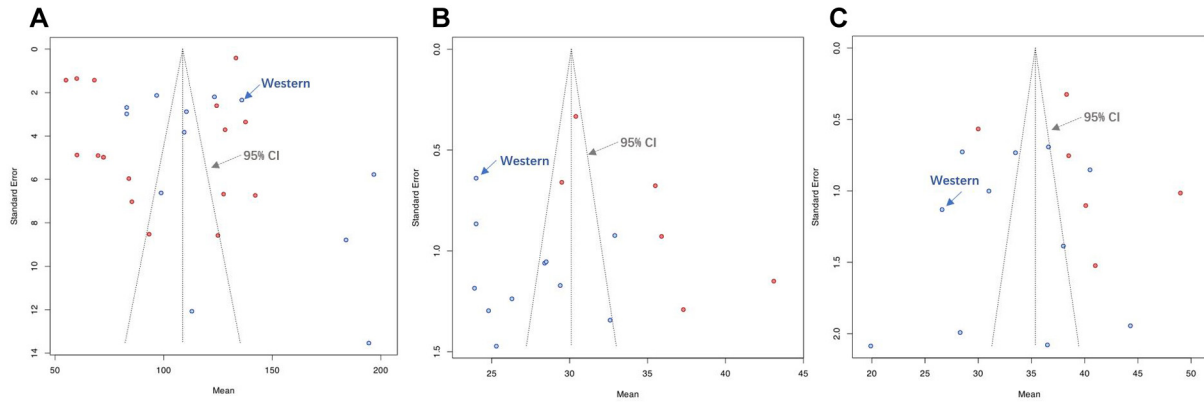
The authors described this tendency for Asian femoral footprints but did not further analyze the underlying reasons. Notably, the 2 earlier studies they compared with were both conducted in Western countries (Norway and the USA).<sup>62,66</sup>

For the tibial footprint, no significant differences were found in either the footprint location or size. In the mediolateral direction, the footprint center was located almost in the middle of the tibial plateau, with a distance of 49% from the medial edge of the tibial plateau for both the Asian and Western groups. In the anteroposterior (AP) direction, there was also no significant difference regarding the footprint center. However, caution should be exercised when interpreting results in the AP direction, as differences in the definition of the anterior tibial ridge across studies may affect the accuracy of the findings. The study by Tsukada et al<sup>83</sup> in the Asian group and by Zantop et al<sup>87</sup> in the Western group applied the Staubli method, while other studies used the Amis and Jakob method<sup>75</sup> (Figure 6). After excluding the 2 studies that used the Staubli method, no significant difference was found between the subgroups.

Our results indicated that, based on the quadrant method, the femoral footprint center in Asians is, on average, 7.9% shallower and 6.4% lower than in Western populations. According to Moon et al,<sup>53</sup> the fitting rectangle for the distal lateral femoral condyle using the quadrant method has a mean length of 44 mm for the longer side and 22 mm for the shorter side. Clinically, this suggests that surgeons should place the ACL footprint approximately 3.5 mm shallower and 1.4 mm lower when performing ACLR for Asian patients to align with native anatomy.

Biomechanically, Brophy et al<sup>3</sup> revealed that a more posteriorly located femoral graft is more susceptible to strain during knee extension and internal rotation, contributing to a higher failure rate in the posterolateral bundle of the ACL graft. Given the significant differences in femoral footprint location across ethnic groups observed in our study, we hypothesized that ACLs in different ethnic groups would experience varying tension at specific knee positions. This warrants further biomechanical testing for verification. A large-scale retrospective study by Navarro et al<sup>59</sup> reported that Asian, Hispanic, and Black patients have a lower ACL revision rate compared with White patients. We propose that differences in femoral insertions between races described in our study may be 1 contributing factor.

Previous biomechanical studies have demonstrated that the position of the femoral footprint significantly influences knee stability and graft tension throughout the range of motion.<sup>44,67</sup> Loh et al<sup>44</sup> showed that altering the femoral tunnel orientation from the 11 o'clock to the 10 o'clock position—closer to the center of the posterolateral (PL) bundle located more anteriorly and distally—resulted in significantly improved knee stability under rotatory loads. Sakane et al<sup>67</sup> showed that the PL bundle, located more anteriorly and distally, exhibits higher in situ force at lower knee flexion angles (0°-45°). In contrast, the AM bundle has a higher in situ force at higher knee flexion angles (45°-90°). Based on these findings, further biomechanical



**Figure 7.** (A) Funnel plot of included studies in the analysis of the femoral footprint size. (B) Funnel plot of included studies in the analysis of the femoral footprint center in the shallow-deep direction. (C) Funnel plot of included studies in the analysis of the femoral footprint center in the high-low direction.

studies focusing on ethnic differences are warranted to investigate the relationship between femoral footprint variation and knee stability.

Another biomechanical study comparing different ethnic populations found that Japanese individuals exhibit a significantly greater knee flexion angle compared with Caucasians.<sup>41</sup> It would then be reasonable to investigate whether the more anterior and distal positioning of the ACL femoral footprint, as observed in the Asian population, could lead to increased knee flexion among Asians.

One concern in the present meta-analysis is the potential selection bias resulting from the mixture of cadaveric-based measurements<sup>¶</sup> and radiological measurements—including plain radiographs<sup>#</sup>, 3D CT,<sup>16,45,76,80</sup> or MRI reconstructions.<sup>10,39,43,74,82</sup> However, previous studies have confirmed that no significant differences exist among these techniques. Lee et al<sup>40</sup> specifically designed a study to verify this, concluding that both plain radiographs and 3D CT images showed highly reliable correlations with anatomic dissection measurements, with no significant differences between the methods.

Han et al<sup>19</sup> found that measuring the ACL footprint with 3D MRI or open cadaveric dissection yielded no significant differences and could be used interchangeably. These findings support the notion that selection bias is limited and acceptable, as both radiographic and direct measurement techniques are included in our meta-analysis.

Notably, the baseline characteristics analysis showed that both groups were highly comparable with respect to sex distribution, mean age, and study methods. Specifically, the percentages of knees in each group, as determined by radiographic methods or direct dissection, were similar. This comparability further mitigates the potential bias originating from the inclusion of studies using different techniques. Funnel plots were also generated to evalu-

ate publication bias (Figure 7). The distributions of studies across all 3 analyses appeared generally symmetrical, suggesting a low likelihood of substantial publication bias in this review. Additionally, several authors have reported that the anatomy of the ACL may vary between men and women.<sup>47,78</sup> Our analysis indicated no significant difference in sex distribution between the 2 groups, further strengthening the reliability of our findings.

This study also has certain limitations. First, because not all included studies were randomized controlled trials or cohort studies with control groups, the evidence level is lower, and only a single-arm meta-analysis could be performed. However, this limitation is inherent in the characteristics of previous studies in this field and represents an external factor. Second, as with any single-arm meta-analysis, some results may exhibit a high amount of statistical heterogeneity.<sup>52,60</sup> The  $I^2$  value in our results indicated that heterogeneity within and between subgroups was significant (>60%). However, because large individual variations in ACL anatomy have been widely reported even within the same ethnic group,<sup>5,9,16,79,85</sup> we believe that the high heterogeneity primarily stems from natural anatomic variations of ACLs among individuals, rather than from the limitations of the meta-analysis. Third, according to the bias assessment of the present study, no included studies were identified as having a high risk of bias.

Despite these internal and external limitations, our study is the first meta-analysis to systematically include all eligible quantitative data on ACL footprints and to demonstrate anatomic differences between Asian and Western populations. We believe that these findings will significantly contribute to the development of more precise anatomic reconstruction techniques in the future.

## CONCLUSION


This meta-analysis demonstrated that the ACL femoral footprint in the Asian population is located more anteriorly and distally than in the Western population, and the

<sup>¶</sup>References 1, 5, 13-15, 20, 26, 28-31, 33, 46, 54, 56, 65, 72, 77, 83, 84, 86, 88.

<sup>#</sup>References 2, 6, 7, 11, 18, 23, 24, 37, 40, 58, 63, 76, 79, 87.

femoral footprint size is smaller. These findings provide valuable insights for population-specific surgical strategies in the future.

## ORCID iD

Dave Yee Han Lee  <https://orcid.org/0000-0002-0379-1130>

## REFERENCES

1. Bedi A, Weber AE, Trasolini NA, et al. Does bone plug and graft orientation (inferior versus posterior) alter native femoral footprint coverage in bone patellar tendon bone anterior cruciate ligament reconstruction? *Arthroscopy*. 2020;36:1875-1881.
2. Bernard M, Hertel P, Hornung H, Cierpinski T. Femoral insertion of the ACL. Radiographic quadrant method. *Am J Knee Surg*. 1997;10:14-21; discussion-2.
3. Brophy RH, Voos JE, Shannon FJ, et al. Changes in the length of virtual anterior cruciate ligament fibers during stability testing: a comparison of conventional single-bundle reconstruction and native anterior cruciate ligament. *Am J Sports Med*. 2008;36:2196-2203.
4. Cheatham SA, Johnson DL. Anatomic revision ACL reconstruction. *Sports Med Arthrosc Rev*. 2010;18:33-39.
5. Colombet P, Robinson J, Christel P, et al. Morphology of anterior cruciate ligament attachments for anatomic reconstruction: a cadaveric dissection and radiographic study. *Arthroscopy*. 2006;22:984-992.
6. Dargel J, Pohl P, Tzikaras P, Koebeke J. Morphometric side-to-side differences in human cruciate ligament insertions. *Surg Radiol Anat*. 2006;28:398-402.
7. Davis AD, Manaqibwala MI, Brown CH Jr, Steiner ME. Height and depth guidelines for anatomic femoral tunnels in anterior cruciate ligament reconstruction: a cadaveric study. *Arthroscopy*. 2016;32:1098-1105.
8. Dienst M, Burks RT, Greis PE. Anatomy and biomechanics of the anterior cruciate ligament. *Orthop Clin North Am*. 2002;33:605-620, v.
9. Dimitriou D, Cheng R, Yang Y, Baumgaertner B, Helmy N, Tsai TY. High variability in anterior cruciate ligament femoral footprint: implications for anatomical anterior cruciate ligament reconstruction. *Knee*. 2021;30:141-147.
10. Dimitriou D, Zou D, Wang Z, Helmy N, Tsai TY. Anterior cruciate ligament bundle insertions vary between ACL-rupture and non-injured knees. *Knee Surg Sports Traumatol Arthrosc*. 2021;29:1164-1172.
11. Doi M, Takahashi M, Abe M, Suzuki D, Nagano A. Lateral radiographic study of the tibial sagittal insertions of the anteromedial and posterolateral bundles of human anterior cruciate ligament. *Knee Surg Sports Traumatol Arthrosc*. 2009;17:347-351.
12. Duthon VB, Barea C, Abrassart S, Fasel JH, Fritschy D, Ménétrey J. Anatomy of the anterior cruciate ligament. *Knee Surg Sports Traumatol Arthrosc*. 2006;14:204-213.
13. Edwards A, Bull AM, Amis AA. The attachments of the anteromedial and posterolateral fibre bundles of the anterior cruciate ligament. Part 2: femoral attachment. *Knee Surg Sports Traumatol Arthrosc*. 2008;16:29-36.
14. Edwards A, Bull AM, Amis AA. The attachments of the anteromedial and posterolateral fibre bundles of the anterior cruciate ligament: part 1: tibial attachment. *Knee Surg Sports Traumatol Arthrosc*. 2007;15:1414-1421.
15. Ferretti M, Ekdahl M, Shen W, Fu FH. Osseous landmarks of the femoral attachment of the anterior cruciate ligament: an anatomic study. *Arthroscopy*. 2007;23(11):1218-1225.
16. Forsythe B, Kopf S, Wong AK, et al. The location of femoral and tibial tunnels in anatomic double-bundle anterior cruciate ligament reconstruction analyzed by three-dimensional computed tomography models. *J Bone Joint Surg Am*. 2010;92:1418-1426.
17. Giuliani JR, Kilcoyne KG, Rue JP, et al. Anterior cruciate ligament anatomy: a review of the anteromedial and posterolateral bundles. *J Knee Surg*. 2009;22:148-154.
18. Guo L, Yang L, Wang AM, Wang XY, Dai G. Roentgenographic measurement study for locating femoral insertion site of anterior cruciate ligament: a cadaveric study with X-Caliper. *Int Orthop*. 2009;33:133-137.
19. Han Y, Kurzenecwyg D, Hart A, Powell T, Martineau PA. Measuring the anterior cruciate ligament's footprints by three-dimensional magnetic resonance imaging. *Knee Surg Sports Traumatol Arthrosc*. 2012;20:986-995.
20. Harner CD, Baek GH, Vogrin TM, Carlin GJ, Kashiwaguchi S, Woo SL. Quantitative analysis of human cruciate ligament insertions. *Arthroscopy*. 1999;15:741-749.
21. Hohmann E, Keough N, Molepo M, Arciero R, Imhoff A. The knee anterolateral ligament is present in 82% of North Americans and 65% of Europeans but only in 46% of Asian studies: a systematic review of frequency and anatomy. *Arthroscopy*. Published online November 5, 2024.
22. Hoy D, Brooks P, Woolf A, et al. Assessing risk of bias in prevalence studies: modification of an existing tool and evidence of interrater agreement. *J Clin Epidemiol*. 2012;65:934-939.
23. Iriuchishima T, Goto B, Fu FH. The radiographic tibial spine area is correlated with the occurrence of ACL injury. *Knee Surg Sports Traumatol Arthrosc*. 2022;30:78-83.
24. Iriuchishima T, Ingham SJ, Tajima G, et al. Evaluation of the tunnel placement in the anatomical double-bundle ACL reconstruction: a cadaver study. *Knee Surg Sports Traumatol Arthrosc*. 2010;18:1226-1231.
25. Iriuchishima T, Ryu K, Aizawa S, Fu FH. Proportional evaluation of anterior cruciate ligament footprint size and knee bony morphology. *Knee Surg Sports Traumatol Arthrosc*. 2015;23:3157-3162.
26. Iriuchishima T, Ryu K, Aizawa S, Fu FH. Size correlation between the tibial anterior cruciate ligament footprint and the tibia plateau. *Knee Surg Sports Traumatol Arthrosc*. 2015; 23:1147-1152.
27. Iriuchishima T, Ryu K, Yorifuji H, Aizawa S, Fu FH. Commonly used ACL autograft areas do not correlate with the size of the ACL footprint or the femoral condyle. *Knee Surg Sports Traumatol Arthrosc*. 2014;22:1573-1579.
28. Iriuchishima T, Shirakura K, Yorifuji H, Aizawa S, Fu FH. Size comparison of ACL footprint and reconstructed auto graft. *Knee Surg Sports Traumatol Arthrosc*. 2013;21:797-803.
29. Iriuchishima T, Shirakura K, Yorifuji H, Aizawa S, Murakami T, Fu FH. ACL footprint size is correlated with the height and area of the lateral wall of femoral intercondylar notch. *Knee Surg Sports Traumatol Arthrosc*. 2013;21:789-796.
30. Iriuchishima T, Suruga M, Yahagi Y, Iwama G, Aizawa S, Fu FH. The location of the femoral ACL footprint center is different depending on the Blumensaat's line morphology. *Knee Surg Sports Traumatol Arthrosc*. 2020;28:2453-2457.
31. Iriuchishima T, Yorifuji H, Aizawa S, Tajima Y, Murakami T, Fu FH. Evaluation of ACL mid-substance cross-sectional area for reconstructed autograft selection. *Knee Surg Sports Traumatol Arthrosc*. 2014;22:207-213.
32. Iwahashi T, Shino K, Nakata K, et al. Direct anterior cruciate ligament insertion to the femur assessed by histology and 3-dimensional volume-rendered computed tomography. *Arthroscopy*. 2010; 26(suppl):S13-S20.
33. Iwama G, Iriuchishima T, Horaguchi T, Aizawa S. Measurement of the whole and midsubstance femoral insertion of the anterior cruciate ligament: the comparison with the elliptically calculated femoral anterior cruciate ligament footprint area. *Indian J Orthop*. 2019;53:727-231.
34. Karlsson J. Anatomy is the key. *Knee Surg Sports Traumatol Arthrosc*. 2010;18:1.
35. Kasten P, Szczodry M, Irrgang J, Kropf E, Costello J, Fu FH. What is the role of intra-operative fluoroscopic measurements to determine tibial tunnel placement in anatomical anterior cruciate ligament reconstruction? *Knee Surg Sports Traumatol Arthrosc*. 2010; 18:1169-1175.

36. Katouda M, Soejima T, Kanazawa T, Tabuchi K, Yamaki K, Nagata K. Relationship between thickness of the anteromedial bundle and thickness of the posterolateral bundle in the normal ACL. *Knee Surg Sports Traumatol Arthrosc.* 2011;19:1293-1298.
37. Kim SH, Lee HJ, Park YB, Jeong HS, Ha CW. Anterior cruciate ligament tibial footprint size as measured on magnetic resonance imaging: does it reliably predict actual size? *Am J Sports Med.* 2018; 46:1877-18884.
38. 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.
39. Lee BH, Seo DY, Bansal S, Kim JH, Ahn JH, Wang JH. Comparative magnetic resonance imaging study of cross-sectional area of anatomic double bundle anterior cruciate ligament reconstruction grafts and the contralateral uninjured knee. *Arthroscopy.* 2016;32:321-329 e1.
40. Lee JK, Lee S, Seong SC, Lee MC. Anatomy of the anterior cruciate ligament insertion sites: comparison of plain radiography and three-dimensional computed tomographic imaging to anatomic dissection. *Knee Surg Sports Traumatol Arthrosc.* 2015;23:2297-2305.
41. Leszko F, Hovinga KR, Lerner AL, Komistek RD, Mahfouz MR. In vivo normal knee kinematics: is ethnicity or gender an influencing factor? *Clin Orthop Relat Res.* 2011; 469:95-106.
42. Li F, Qin L, Gong X, et al. The Chinese ACL injury population has a higher proportion of small ACL tibial insertion sizes than Western patients. *Knee Surg Sports Traumatol Arthrosc.* 2020;28:888-896.
43. Lin J, Zhang S, Xin E, Liang M, Yang L, Chen J. Anterior cruciate ligament femoral footprint is oblong-ovate, triangular, or two-tears shaped in healthy young adults: three-dimensional MRI analysis. *Knee Surg Sports Traumatol Arthrosc.* 2023;31:5514-5523.
44. Loh JC, Fukuda Y, Tsuda E, Steadman RJ, Fu FH, Woo SL. Knee stability and graft function following anterior cruciate ligament reconstruction: comparison between 11 o'clock and 10 o'clock femoral tunnel placement. 2002 Richard O'Connor Award paper. *Arthroscopy.* 2003; 19:297-304.
45. Lorenz S, Elser F, Mitterer M, Obst T, Imhoff AB. Radiologic evaluation of the insertion sites of the 2 functional bundles of the anterior cruciate ligament using 3-dimensional computed tomography. *Am J Sports Med.* 2009;37:2368-2376.
46. Luites JW, Wymenga AB, Blankevoort L, Kooloos JG. Description of the attachment geometry of the anteromedial and posterolateral bundles of the ACL from arthroscopic perspective for anatomical tunnel placement. *Knee Surg Sports Traumatol Arthrosc.* 2007; 15:1422-1431.
47. McClay Davis I, Ireland ML. ACL injuries—the gender bias. *J Orthop Sports Phys Ther.* 2003;33:A2-A8.
48. McGuire DA, Hendricks SD. Allograft tissue in ACL reconstruction. *Sports Med Arthrosc Rev.* 2009;17:224-233.
49. Middleton KK, Muller B, Araujo PH, et al. Is the native ACL insertion site "completely restored" using an individualized approach to single-bundle ACL-R? *Knee Surg Sports Traumatol Arthrosc.* 2015;23:2145-2150.
50. Mochizuki T, Fujishiro H, Nimura A, et al. Anatomic and histologic analysis of the mid-substance and fan-like extension fibres of the anterior cruciate ligament during knee motion, with special reference to the femoral attachment. *Knee Surg Sports Traumatol Arthrosc.* 2014;22:336-44.
51. Mochizuki T, Muneta T, Nagase T, Shirasawa S, Akita KI, Sekiya I. Cadaveric knee observation study for describing anatomic femoral tunnel placement for two-bundle anterior cruciate ligament reconstruction. *Arthroscopy.* 2006;22:356-361.
52. Mogire RM, Mutua A, Kimita W, et al. Prevalence of vitamin D deficiency in Africa: a systematic review and meta-analysis. *Lancet Glob Health.* 2020;8:e134-e42.
53. Moon DK, Jo HS, Lee DY, et al. Anterior cruciate ligament femoral-tunnel drilling through an anteromedial portal: 3-dimensional plane drilling angle affects tunnel length relative to notchplasty. *Knee Surg Relat Res.* 2021;33:13.
54. Morales-Avalos R, Perelli S, Vilchez-Cavazos F, et al. The morphology of the femoral footprint of the anterior cruciate ligament changes with aging from a large semicircular shape to a small flat ribbon-like shape. *Knee Surg Sports Traumatol Arthrosc.* 2022; 30:3402-3413.
55. Morales-Avalos R, Torres-González EM, Padilla-Medina JR, Monllau JC. ACL anatomy: is there still something to learn? *Rev Esp Cir Ortop Traumatol.* 2024, 68:T422-T427.
56. Muneta T, Takakuda K, Yamamoto H. Intercondylar notch width and its relation to the configuration and cross-sectional area of the anterior cruciate ligament. A cadaveric knee study. *Am J Sports Med.* 1997;25:69-72.
57. Muro S, Kim J, Tsukada S, Akita K. Significance of the broad non-bony attachments of the anterior cruciate ligament on the tibial side. *Sci Rep.* 2022;12:6844.
58. Musahl V, Burkart A, Debski RE, Van Scyoc A, Fu FH, Woo SL. Anterior cruciate ligament tunnel placement: comparison of insertion site anatomy with the guidelines of a computer-assisted surgical system. *Arthroscopy.* 2003;19:154-160.
59. Navarro RA, Prentice HA, Inacio MCS, Wyatt R, Maletis GB. The association between race/ethnicity and revision following ACL reconstruction in a universally insured cohort. *J Bone Joint Surg Am.* 2019;101:1546-1253.
60. Noubiap JJ, Nansseu JR, Nyaga UF, et al. Global prevalence of diabetes in active tuberculosis: a systematic review and meta-analysis of data from 2.3 million patients with tuberculosis. *Lancet Glob Health.* 2019;7:e448-e60.
61. Ow ZGW, Cheong CK, Hai HH, et al. Securing transplanted meniscal allografts using bone plugs results in lower risks of graft failure and reoperations: a meta-analysis. *Am J Sports Med.* 2022;50:4008-4018.
62. Parkar AP, Adriaensen M, Vindfeld S, Solheim E. The anatomic centers of the femoral and tibial insertions of the anterior cruciate ligament: a systematic review of imaging and cadaveric studies reporting normal center locations. *Am J Sports Med.* 2017;45:2180-2188.
63. Pietrini SD, Ziegler CG, Anderson CJ, et al. Radiographic landmarks for tunnel positioning in double-bundle ACL reconstructions. *Knee Surg Sports Traumatol Arthrosc.* 2011;19:792-800.
64. Provencher MT, Ryu JH, Gaston T, Dewing CB. Technique: bone-patellar tendon-bone autograft ACL reconstruction in the young, active patient. *J Knee Surg.* 2011;24:83-92.
65. Pujol N, Queinsec S, Boisrenoult P, Maqdes A, Beaufils P. Anatomy of the anterior cruciate ligament related to hamstring tendon grafts. A cadaveric study. *Knee.* 2013;20:511-514.
66. Rahnemai-Azar AA, Sabzevari S, Irrarázaval S, Chao T, Fu FH. Anatomical individualized ACL reconstruction. *Arch Bone Jt Surg.* 2016;4:291-297.
67. Sakane M, Fox RJ, Woo SL, Livesay GA, Li G, Fu FH. In situ forces in the anterior cruciate ligament and its bundles in response to anterior tibial loads. *J Orthop Res.* 1997;15:285-293.
68. Samitier G, Marcano AI, Alentorn-Geli E, Cugat R, Farmer KW, Moser MW. Failure of anterior cruciate ligament reconstruction. *Arch Bone Jt Surg.* 2015;3:220-240.
69. Sasaki N, Ishibashi Y, Tsuda E, et al. The femoral insertion of the anterior cruciate ligament: discrepancy between macroscopic and histological observations. *Arthroscopy.* 2012; 28:1135-1146.
70. Schreiber VM, van Eck CF, Fu FH. Anatomic double-bundle ACL reconstruction. *Sports Med Arthrosc Rev.* 2010;18:27-32.
71. Siebold R. Flat ACL anatomy: fact no fiction. *Knee Surg Sports Traumatol Arthrosc.* 2015; 23:3133-1335.
72. Siebold R, Ellert T, Metz S, Metz J. Femoral insertions of the anteromedial and posterolateral bundles of the anterior cruciate ligament: morphometry and arthroscopic orientation models for double-bundle bone tunnel placement—a cadaver study. *Arthroscopy.* 2008;24:585-592.
73. Siebold R, Ellert T, Metz S, Metz J. Tibial insertions of the anteromedial and posterolateral bundles of the anterior cruciate ligament: morphometry, arthroscopic landmarks, and orientation model for bone tunnel placement. *Arthroscopy.* 2008;24:154-161.

74. Sivakumaran T, Jaffer R, Marwan Y, et al. Reliability of anatomic bony landmark localization of the ACL femoral footprint using 3D MRI. *Orthop J Sports Med* 2021; 9:23259671211042603.
75. Sullivan JP, Cook S, Gao Y, Wolf BR. Radiographic anatomy of the native anterior cruciate ligament: a systematic review. *HSS J*. 2015;11:154-165.
76. Suruga M, Horaguchi T, Iriuchishima T, et al. The correlation between the femoral anterior cruciate ligament footprint area and the morphology of the distal femur: three-dimensional CT evaluation in cadaveric knees. *Eur J Orthop Surg Traumatol*. 2019;29:849-854.
77. Suruga M, Horaguchi T, Iriuchishima T, et al. Morphological size evaluation of the mid-substance insertion areas and the fan-like extension fibers in the femoral ACL footprint. *Arch Orthop Trauma Surg*. 2017;137:1107-1113.
78. Sutton KM, Bullock JM. Anterior cruciate ligament rupture: differences between males and females. *J Am Acad Orthop Surg*. 2013;21:41-50.
79. Takahashi M. Anatomical study of the femoral and tibial insertions of the anteromedial and posterolateral bundles of human anterior cruciate ligament. *Am J Sports Med*. 2005;34:787-792.
80. Tampere T, Van Hoof T, Cromheeecke M, et al. The anterior cruciate ligament: a study on its bony and soft tissue anatomy using novel 3D CT technology. *Knee Surg Sports Traumatol Arthrosc*. 2017;25:236-244.
81. Tanaka Y, Shiozaki Y, Yonetani Y, Kanamoto T, Tsujii A, Horibe S. MRI analysis of the attachment of the anteromedial and posterolateral bundles of anterior cruciate ligament using coronal oblique images. *Knee Surg Sports Traumatol Arthrosc*. 2011;19(suppl 1):S54-S59.
82. Tashiro Y, Lucidi GA, Gale T, et al. Anterior cruciate ligament tibial insertion site is elliptical or triangular shaped in healthy young adults: high-resolution 3-T MRI analysis. *Knee Surg Sports Traumatol Arthrosc*. 2018, 26:485-490.
83. Tsukada H, Ishibashi Y, Tsuda E, Fukuda A, Toh S. Anatomical analysis of the anterior cruciate ligament femoral and tibial footprints. *J Orthop Sci*. 2008;13:122-129.
84. Yahagi Y, Horaguchi T, Iriuchishima T, Suruga M, Iwama G, Aizawa S. Correlation between the mid-substance cross-sectional anterior cruciate ligament size and the knee osseous morphology. *Eur J Orthop Surg Traumatol*. 2020;30:291-296.
85. Yahagi Y, Iriuchishima T, Horaguchi T, Suruga M, Tokuhashi Y, Aizawa S. The importance of Blumensaat's line morphology for accurate femoral ACL footprint evaluation using the quadrant method. *Knee Surg Sports Traumatol Arthrosc*. 2018;26:455-461.
86. You T, Zhang X, Zhang W, Jiang C, Huang W, Li W, Zhang H, Bai L, Jiang X, Zuo J, Chen P, Ren S: [Anatomical research of tibial insertion of anterior cruciate ligament in Chinese adults]. *Zhongguo Xiu Fu Chong Jian Wai Ke Za Zhi*. 2015;29:730-733.
87. Zantop T, Wellmann M, Fu FH, Petersen W. Tunnel positioning of anteromedial and posterolateral bundles in anatomic anterior cruciate ligament reconstruction: anatomic and radiographic findings. *Am J Sports Med*. 2008;36:65-72.
88. Zauleck MK, Gabriel S, Fischmeister MF, Hirtler L: Origin of the anterior cruciate ligament and the surrounding osseous landmarks of the femur. *Clin Anat*. 2014;27:1103-1110.