Radiographic Anatomy of the Native Anterior Cruciate Ligament: a Systematic Review

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Received: 30 June 2014/Accepted: 3 September 2014/Published online: 2 December 2014
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Abstract *Background:* In an attempt to improve the accuracy and reproducibility of tunnel positioning, radiographs are being analyzed in an attempt to recreate the native anatomy of the ACL. Understanding the native ACL radiographic anatomy is an essential prerequisite to understand the relevance of postoperative tunnel position. *Questions/Purposes:* We performed a systematic review of the literature to delineate the radiographic location of the native ACL femoral and tibial footprints. *Methods:* A search was performed in March 2014 in PubMed, the Cochrane Collaboration Library, and EMBASE to identify all studies that evaluated the native anterior cruciate ligament (ACL) anatomy on radiographs. Various measurement methods were used in each study, and averages were obtained of the data from studies with the same measurement methods. *Results:* Fifteen papers were identified (which included data on 177 femora and 207 tibiae in total). Evaluation of the femoral footprint using the quadrant method on lateral knee radiographs showed that the average percent distance location of the anteromedial (AM) bundle and posterolateral (PL) bundle was 22.8% (95% confidence interval (CI) 16.59–28.90) and 32.5% (95% CI 27.71–37.26) from the posterior condyle, respectively, and 23.2% (95% CI 19.52–26.94) and 50.0%

(95% CI 46.16–53.76) from Blumensaat's line, respectively. Using the Amis and Jacob method, the tibial footprint on the lateral knee radiograph average percent distances was 35.1% (95% CI 34.46–35.72) for the center of the AM bundle and 47.3% (95% CI 41.69–52.95) for the center of the PL bundle of the ACL. The femoral and tibial ACL footprints on the anteroposterior (AP) views of the knee were not well delineated by these studies. *Conclusion:* The information presented in this systematic review offers surgeons another important tool for accurate ACL footprint identification.

Keywords systematic review · anterior cruciate ligament · footprint · radiograph · anatomy

Introduction

Several studies report that greater than 50% of ACL reconstruction failures occur as a result of technical considerations [4, 7, 13, 26]. The largest such study, Multicenter ACL Revision Study (MARS), reported that technical error accounted for ACL reconstruction failure in 24% of patients, which was second only to acute trauma (37%) [29]. Garofalo et al. demonstrated femoral tunnel malposition in 79% of their cases and tibial tunnel malposition in 21% of their cases of revision ACL reconstruction [9]. Taggart et al. reported a series of revision ACL reconstruction cases with femoral tunnel malposition in 12/20 (60%) [24]. The MARS study reported femoral tunnel malposition in 80% (223 patients) of the cases and tibial tunnel malposition in 37% (104 patients) of the cases [29]. Based upon these studies, it is clear that ACL tunnel malposition is a common etiology for failure.

The ideal tunnel position for ACL reconstruction is an ongoing debate. It is generally agreed upon that attempting to reconstruct the patient's native anatomy is the ideal approach [17, 18, 20, 30]. Patient-specific reconstruction includes evaluating the size and shape of the patient's femoral notch, ACL footprints on the femur and tibia, and the interplaying relationship between those three entities and

Electronic supplementary material The online version of this article (doi:10.1007/s11420-014-9417-5) contains supplementary material, which is available to authorized users.

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the ACL reconstruction graft. If the native ACL footprint can be identified, then the surgeon has improved ability to reconstruct the ligament based upon patient-specific anatomy. In the setting of a chronic ACL tear or a revision ACL reconstruction, the surgeon must rely on alternative anatomical landmarks. On the tibial side, the ACL footprint is approximately 10 mm anterior to the PCL, bisected with the anterior horn of the lateral meniscus, and just lateral to the medial tibial eminence. The femur has fewer and less distinct landmarks, which make it more challenging to define a uniform location for the ideal ACL reconstruction.

The ideal scenario is to have landmarks on the femur and the tibia that are independent of the footprints to improve reproducibility. The footprints are gone in revision surgery, may be obscured by the initial injury, and are frequently removed in order to visualize the junction of the notch with the back wall in order to prevent back wall break through when drilling the tunnel. Anatomical dissection studies have been important to help us understand the location of the ACL; however, the exposure achieved for anatomical dissection is substantially different than the exposure for arthroscopic-assisted ACL reconstruction, and exact measurements are not feasible with limited exposure. Radiographic methods are appealing because the derived information can be used intraoperatively to confirm appropriate tunnel placement and postoperatively to evaluate the accuracy of tunnel placement.

In an attempt to improve the accuracy and reproducibility of tunnel positioning, radiographs are being analyzed in an attempt to recreate the native anatomy of the ACL. Understanding the native ACL radiographic anatomy is an essential prerequisite to understand the relevance of postoperative tunnel position. We performed a systematic review of the literature to (1) identify measurement systems to localize the native ACL based upon the best available evidence, (2) identify the center point location of the native ACL on radiographs based upon these measurement systems, (3) and propose that the most commonly studied measurement systems should be used as a gold standard for clinical practice and research.

Methods

A literature search was performed on March 3, 2014 in PubMed, the Cochrane Collaboration Library, and EMBASE for “anterior cruciate ligament AND radiograph* AND anatomy.” The database search resulted a yield of 644 total studies. The abstracts of all articles found in the search were read to identify studies that evaluated the radiographic anatomy of the native ACL. Since all three search terms are fairly common, there were a large number of the studies that did not evaluate the native ACL footprint on plain radiographs, and these studies were excluded because they were not relevant to the study. Inclusion criteria included all articles that studied the native ACL footprint anatomy on plain radiographs or fluoroscopy by way of radiopaque markers (Fig. 1). The bibliographies of the included studies were reviewed to search for additional articles that may have

been missed on the initial searches. Fifteen studies were identified in the search that met inclusion criteria [2, 3, 5, 6, 8, 10–12, 14–16, 19, 23, 25, 31].

Each of the 15 studies was then broken down into groups based upon the radiographs used for measurements and the measurement system utilized in the study. When the methods of each of the 15 studies identified in our search were the same for the radiographic view and measurement systems, we combined the data in order to perform a meta-analysis. The radiographic studies commonly used were anteroposterior (AP) and lateral radiographs of the knee. Various measurement methods were identified in the 15 studies identified in our search, and the measurements are discussed in detail in the “Results” section of the paper.

The statistical analysis was done using a continuous random effects model with OpenMetaAnalyst software. Quantitative synthesis weighted averages and associated 95% confidence intervals were calculated by a statistician [28]. These results were then analyzed by the same statistician for appropriate accuracy and precision. We identified a gold standard location for the center of the ACL footprint on the tibia and the femur by identifying the weighted average locations for the ACL femoral and tibial footprints.

Results

Specimens

The knees evaluated were from a wide range of ages with various methods of preparation and measurement systems. The combined total from all studies included 177 femora and 207 tibiae. All of the studies evaluated were done on cadaveric specimens with an intact ACL with the exception of Kasten et al. [14] who studied the acutely torn ACL tibial footprint intraoperatively of 67 patients. All of the studies evaluated unpaired specimens with the exception of Dargel et al. [6], who used paired specimens to evaluate side-to-side differences in 30 cadaveric knees. Some of the studies in the current literature search identified the ACL as a single entity [3, 10, 16], yet the majority divided the ACL into separate bundles [5, 8, 11, 14, 19, 25, 31]. Division of the ACL into distinct bundles, anteromedial (AM) and posterolateral (PL), was typically done by observing the variation in tightness between the two bundles in flexion versus extension after removing the synovial tissue overlying the tendon. After the ACL was identified, each of the studies used a radiopaque marker to delineate the footprint.

Femoral Footprint Measurement Methods and Results

Lateral Knee Radiographs of the Femur

The femoral footprint of the native ACL was measured in various methods. The most common methodology was first described by Bernard and is known as the “quadrant method” [3]; however, the description is actually a “grid” rather than a “quadrant” system. The quadrant method of measurement is done by obtaining a lateral radiograph of the knee with the femoral condyles superimposed. A line is drawn

Fig. 1. Selection process for systematic review.

along Blumensaat's line with a parallel line drawn tangent to the distal lateral femoral condyle. Perpendicular lines are then drawn along the dorsal and ventral border of the condyle where the proximal line (extension of Blumensaat's line) crossed the condyles. Measurements from the center of the ACL and/or ACL bundles are then done in terms of percentages of the grid described from the posterior condyle and from Blumensaat's line (Fig. 2). Eight different studies used the quadrant method to measure the location of the native ACL anatomy on radiographs (Table 1).

For single-bundle analysis, the femoral footprint percent distances were similar for the percent distances of the ACL from the posterior condylar line at 26.9% (8 cadaveric knees) [16] and 24.8% (10 cadaveric knees) [3] in two of the studies, but the third reported 43.1% (16 cadaveric knees) [10]. The percent distances from Blumensaat's line were reported as 27.5% (8 cadaveric knees) [16], 28.5% (10 cadaveric knees) [3], and 38.3% (16 cadaveric knees) [10]. The quantitative synthesis weighted average center point location of the single-bundle analysis was 31.6% from the posterior condyle and 31.5% from Blumensaat's line (see Table 1 and Fig. 3).

The double-bundle measurements were measured from the centers of the AM and PL bundles, although some studies [5, 19] further define the area of the footprint of the AM and PL bundles (Table 1). The percent distance of the AM bundle from the posterior condylar line ranged from 15% (15 cadaveric knees) [11] to 31.9% (32 cadaveric knees) [25]. The average AM bundle percent distance from Blumensaat's line varied from 14.6% (12 cadaveric knees) [19] to 26.9% (32 cadaveric knees) [25]. The PL bundle percent distance from the posterior condylar line ranged from 28.9% (12 cadaveric knees) [19] to 39.8% (32 cadaveric knees) [25]. The percent distance of the PL bundle from Blumensaat's line had an average range from 42.3% (12 cadaveric knees) [5] to 53.6% (20 cadaveric knees) [31]. The quantitative synthesis weighted average center point

location of the AM bundle and PL bundle was 22.8 and 32.5% from the posterior condyle, respectively, and 23.2 and 5,150.0% from Blumensaat's line, respectively (Table 1 and Fig. 3).

Additionally, several studies have shown that the AM and PL bundles are horizontally aligned with the knee flexed greater than 90° on the knee lateral radiograph [19, 21, 23]. Pietrini et al. showed that 115° of flexion was the point at which the bundles were aligned horizontally to the plane of the ground [19].

Guo described a complex parallelogram that allowed femoral ACL measurements on the lateral radiograph which are percentages similar to those described by Bernard [3]. Using 16 cadaveric specimens, he found that the average was 2:3 for the distance from Blumensaat's line and 13:7 for the distance from the femoral axis (Fig. 4) [10].

AP/PA Knee Radiographs of the Femur

Only 4 of the 15 studies evaluated the ACL femoral footprint on AP/posteroanterior (PA) radiographs [2, 10, 15, 19]. For the AP/PA measurement of the femur, a clock face analogy was used by Guo et al. and Berg et al. to describe the location of the femoral footprint [2, 10]. The “time” on the clock pointed to the location of the ACL. Guo et al. divided the ACL footprint evenly into five sections on the radiographs and then measured the angle based upon a clock face metric [10]. The averages for his 16 cadaveric knees (all radiographs flipped to appear like a right knee) had the superior edge at 10.4+−1.25, midway superior 10.0+−1.05, center 9.7+−0.62, midway inferior to center 9.2+−0.35, and the inferior edge at 8.1+−0.40 o'clock [10]. Berg et al. reported that with the knee in 50° of flexion, the ACL femoral attachment was at the 11 o'clock position on right knees and 1 o'clock position on left knees [2]. Linter et al. evaluated the ACL from the AP and found that only with the knee flexed greater than 60° could the ACL footprint be

Fig. 2. The quadrant method (described by Bernard et al.) A line is drawn along Blumensaat's line with a parallel line drawn tangent to the distal lateral femoral condyle. Perpendicular lines are then drawn along the dorsal and ventral border of the condyle where the proximal line (extension of Blumensaat's line) crossed the condyles. Measurements from the center of the ACL and/or ACL bundles are then done in terms of percentages of the grid described from the posterior condyle and from Blumensaat's line.

adequately visualized in the notch [15]. They report that the footprint covered 66% of the notch lateral to midline (range 45–75%) [15]. Pietrini et al. reported notch height and percent of maximum height of the intercondylar notch of the AM and PL bundles with full extension and 55° and 90° of flexion in contrast to the clock face analog [19]. At 55° of flexion, the AM and PL bundles were located 11.9 and 39.8%, respectively, distal to the notch roof. At 90° of knee flexion, the AM bundle center was located at 18.4% and the PL bundle center at 39.1% of the maximum height of the intercondylar notch relative to the notch roof (Fig. 5) [19].

Tibial Footprint Measurement Methods and Results

Lateral Knee Radiographs of the Tibia

The majority of quantitative measurements of the ACL footprint of the tibia were calculated on the lateral view of the knee [5, 8, 14, 16, 19], compared to two studies that evaluated the AP view [15, 19] of the knee. The most commonly used lateral radiographic measurements were described by Amis and Jakob [1], which were used in five studies (Table 2). The center of the ACL bundles is measured along a line that is drawn parallel to the medial tibial plateau, passing through the posteriormost corner of the tibial plateau (Fig. 6). The Amis and Jakob measurements were combined from each study, and the resultant quantitative synthesis weighted average was 35.1% for the center of the AM bundle and 47.3% for the center of the PL bundle of the ACL, measured from anterior (Fig. 6). Staubli and Rauschnig described a measurement system in which the ACL is expressed as the total AP diameter of the tibia that is perpendicular to the tibial axis which was used in two

studies (Fig. 7) [22]. The average center of the AM bundle using the Staubli and Rauschnig method when the two studies were combined resulted in 30.4% for the center of the AM bundle and 47.0% for the center of the posterolateral bundle (Fig. 7 and Table 3). Of note, Kasten et al. reported intraoperative radiographic measurements on patients with an acutely torn ACL by placing a Kirschner wire in the center of the AM and PL bundles on the tibia after careful debridement of the torn ACL stump, and then obtaining lateral radiographs of the knee [14].

AP Knee Radiographs of the Tibia

Two of the 12 studies evaluated the native ACL footprint on the tibia on the AP radiograph of the knee. Lintner et al. studied seven cadaveric knees in total and found that the center of the tibial insertion is just lateral to the anatomic center of the tibia with an average of 49% from the lateral edge [15]. They state that the tibial insertion covers the apex and lateral face of the medial intercondylar eminence, but there are no measurements reported for comparison of the width of the footprint on the AP radiograph. For a double-bundle analysis, Pietrini et al. measured parallel to the maximum coronal diameter of the tibia and found that the center of the AM bundle was $44.2 \pm 3.4\%$ from the medial aspect of the tibia, while the position of the PL bundle center was $50.1 \pm 2.1\%$ (Fig. 5) [19].

Other Notable Radiographic Measurements

There were several outlier measurement systems that should be recognized. Dargel et al. compared side-to-side anatomy of the ACL for the purpose of preoperative planning [6].

Table 1 Femoral measurements—Bernard's quadrant method

Quadrant method measurements on femoral condyle	Center of AM bundle, % distance from posterior condylar line (95% CI)	Center of the AM bundle, % distance from Blumensaat's line (95% CI)	Center of PL bundle, % distance from posterior condylar line (95% CI)	Center of the PL bundle, % distance from Blumensaat's line (95% CI)	Entire ACL single bundle ACL % distance from posterior condylar line (95% CI)	Entire ACL single bundle % distance from Blumensaat's line (95% CI)
Iriuchishma 2010; 15 cadaveric knees	15±6% (11.96–18.04)	26±8% (21.95–30.05)	32±9% (27.45–36.55)	52±5% (49.47–54.53)		
Zantrop 2008; 20 cadaveric knees	18.5±4.73% ^a (16.43–20.57)	22.3±6.63% ^a (19.39–25.21)	29.3±5.83% ^a (26.75–31.86)	53.6±5.83% ^a (51.04–56.16)		
Colombet 2006; 7 cadaveric knees	26.4±2.6% (24.47–28.33)	25.3±4.2% (22.19–28.41)	32.2±3.9% (29.31–35.09)	47.6±6.5% (42.78–52.42)		
Takahashi 32 cadaveric knees	31.9±4.73% ^a (30.26–33.54)	26.9±6.63% ^a (24.60–29.19)	39.8±5.83% ^a (29.31–35.09)	53.2±5.83% ^a (51.18–55.22)		
Guo 2009; 16 cadaveric knees					43.1±4.6% (40.85–45.35)	38.3±1.3% (37.66–38.94)
Musahl 2003; 8 cadaveric knees					26.9±3.5% (24.47–29.32)	27.5±3.2% (25.28–29.72)
Bernard 1997; 10 cadaveric knees					24.8±4.05% ^a (22.29–27.31)	28.5±2.25% ^a (25.71–31.29)
Pietrini 2011; 12 cadaveric knees	21.6±5.6% (18.43–24.77)	14.6±7.7% (10.24–18.96)	28.9±4.6% (26.29–31.50)	42.3±6.0% (38.91–45.69)		
Quantitative Synthesis Mean(95% CI)	22.75% (16.59–28.90)	23.23% (19.52–26.94)	32.48% (27.71–37.26)	49.96% (46.16–53.76)	31.61% (19.98–43.24)	31.50% (23.27–39.73)

All results are in percentages. Quantitative synthesis mean results evaluated by a continuous random effects model using OpenMetaAnalyst software. Results in parentheses are 95% CI
 CI confidence interval

^a Calculated standard deviation measurements from similar studies. ±SD

Fig. 3. Drawing done to scale demonstrating the weighted average center point location of the ACL footprint using the quadrant method. *Red*=anteromedial bundle, *blue*=posterolateral bundle, and *black*=single bundle. The grey box represents the area from which the measurements are taken. See Table 1 for specific percent measurement data (Color figure online).

They used radiopaque barium painted onto the femoral and tibial footprints. The contralateral specimens were mirrored and overlapped, and the areas of the intersection were digitally determined. The average intersection area was only 31.4% for the femoral footprint with an average distance between the center of gravity of 4.7 ± 2.56 mm. The tibial footprint had an average intersection area of only 33.4% with an average distance between the center of gravity of 4.5 ± 1.95 mm.

Pietrini et al. also performed axial measurements of the tibia (Fig. 5) [19]. The center of the AM bundle was 48% along the maximum coronal diameter of the axial sections starting medially and 37.7% in reference to the anterior edge of the tibia along the maximum sagittal diameter. The PL bundle was 51.2% with respect to the medial tibial margin along the coronal diameter and 51.8% in reference to the anterior edge of the tibia in the sagittal plane.

Intraobserver and Interobserver Reliability of Measurements

Intraobserver and interobserver reliability using single-measure intraclass correlation coefficients (ICCs) was evaluated in only one study [19]. Pietrini et al. evaluated the overall combined reliability in measuring the AM and PL footprint on radiographs. Three observers of differing experience levels were found to have nearly perfect reliability with ICC scores of .989, .993, and .989 with a combined ICC for interobserver reliability of .990 [19]. No other

papers were identified that describe the reliability of measurements.

Discussion

Radiographs remain an attractive option to evaluate tunnel position in ACL reconstruction. Radiographs are cost-efficient and almost universally available as a screening tool that is already in use for routine follow-up. Ideally, radiographs would allow surgeons to evaluate ACL tunnel position both intraoperatively and postoperatively. Intraoperative fluoroscopy is readily available and allows for the evaluation of guide wire position prior to reaming an ACL tunnel to prevent tunnel malposition, which is one of the most commonly cited reasons for ACL reconstruction failure. There are other more accurate methods to evaluate three-dimensional structure such as CT and MR. However, CT has increased radiation exposure and is more difficult to obtain intraoperatively, and MRI does not allow for intraoperative guidance. In order to eliminate the problem of ACL tunnel malposition using radiographs, first, it must be shown that plain radiographs can identify the location of where the tunnel should be, and second, it must be shown that the methods for measurements are reliable.

Our review has limitations. A weakness of the study is that it operates under the assumption that the knees studied represent the general population and that the calculated

Fig. 4. Parallelogram described by Guo et al. Complex parallelogram taking into account the axis of the femur and the posterior condyle along with a line overlying Blumensaat's line and the distal aspect of the condyle. Result in ratio form: 2:3 for the distance from Blumensaat's line and 13:7 for the distance from the femoral axis.

average for the central location of the ACL footprint is the ideal position for future ACL reconstructions. Another major limitation of the study is that there is limited reliability data reported for the measurements. The intraobserver and interobserver reliability results for the radiographic measurements reported by Pietrini et al. were near perfect [19]. However, they do not report the reliability of specific measurements but report the reliability of all combined measurements together for three observers of various levels of experience on two separate occasions at least 2 weeks apart. It is therefore unknown if some of the measurements had poor reliability masked by the majority of the measurements that had excellent reliability in the overall calculations. In our systematic review, this is the only paper evaluating intraobserver and interobserver reliability of ACL radiographic measurements and needs to be further studied.

Our summary results describe the best available evidence for radiographic identification of the center of the ACL footprint (Table 4). We chose to identify a single point for the center of the ACL single or double bundles rather than the area of the footprint because it is directly relevant to the technique of ACL reconstruction. Each time an ACL reconstruction is performed, a center point has to be chosen for the tunnel and it makes sense that the center of the footprint would be a logical location for the center of the tunnel to be reamed. The ACL footprint, however, is not a perfect circle,

and it is therefore possible that the center of the footprint is not necessarily the ideal location for the reconstruction. In addition, the tunnel is reamed through the femur and the tibia obliquely and therefore creates an oval rather than a circle. Regardless, the current trend is to reconstruct the ACL as close to the patient's anatomy as possible, and it is assumed that the center of the ACL footprint is the best fit position. We therefore chose to identify the center of the footprint on radiographs so that the information could be directly applicable to identifying a single point on fluoroscopy or radiographs for the center of the ACL tunnel.

We propose that the most commonly studied measurement systems that identify the center of the ACL footprints for single- and double-bundle reconstructions should be the gold standard for clinical practice and research (Table 4). The gold standard is not necessarily the perfect test, but merely the best available test. As science increases its hold on the practice of medicine, we become more aware of the limitations of the clinical methods. Gold standards are in a perpetual evolution and by definition are almost never reached. They are constantly challenged and superseded when appropriate [27]. The following measurements have excellent intrarater and interrater reliability as reported by one study and have been studied the most in the literature, making them the gold standard for future comparison. The results identified are building blocks in the infancy of

Fig. 5. “With kind permission from Springer Science+Business Media: Knee Surgery, Sports Traumatology, Arthroscopy, Radiographic landmarks for tunnel positioning in double-bundle ACL reconstructions, 19, 2011,792–800, Pietrini et al., Figs 2 & 3.” Top row: **a** PA notch view and **b** lateral knee (femur). Bottom row: **a** AP knee (tibia), **b** lateral knee (tibia), and **c** axial tibia; *AM* center of the anteromedial bundle attachment, *PL* center of the posterolateral bundle attachment, *H* maximum height of the intercondylar notch, *B* maximum sagittal diameter of the lateral femoral condyle along Blumensaat’s line, *B_p* anterior–posterior distance drawn from the bundle centers to the most dorsal subchondral contour and running parallel to line Blumensaat’s line, *H_p* proximal–distal distance drawn from the bundle centers to Blumensaat’s line and running parallel to line *H*, *PC* posterior femoral cortex, *LIE* lateral intercondylar eminence, *MIE* medial intercondylar eminence, *AHLM* anterior horn of the lateral meniscus, *AHMM* anterior horn of the medial meniscus, *PHLM* posterior horn of the lateral meniscus, *PHMM* posterior horn of the medial meniscus, *CD* maximum coronal diameter of the tibia plateau, *SD* maximum sagittal diameter of the tibial plateau [26].

development, and future studies will corroborate or refute the hypothesis tested in this study. Nonetheless, the results provide a framework for clinical practice that is the best available evidence to date on the location of the central point of the ACL on plain radiographs.

There are essentially three measurement systems that we propose to be the gold standard for identifying the center of

the ACL footprint on plain radiographs (either for the center for the entire ACL or for the center for the AM and PL bundles). They include the Bernard grid method for the femoral tunnel [3], the Amis and Jakob method to identify the tibial tunnel on the lateral radiograph of the femur [1], and the AP measurement of the tibia as a percent from medial to lateral [15, 19]. We have reduced the gold standard

Table 2 Tibial measurements—Amis and Jakob method

Amis and Jakob line, % distance from anterior of total distance	Center of AM bundle, % distance from anterior tibia (95% CI)	Center of PL bundle, % distance from anterior tibia (95% CI)	Center of entire ACL, % distance from anterior tibia (95% CI)
Kasten 2010; 67 knees	35±3.17% ^a (34.24–35.76)	48±3.17% ^a (47.24–48.76)	
Doi 2009; 31 cadaveric knees	34.6±4.3% (33.09–36.11)	38.5±4.3% (36.99–40.01)	
Colombet 2006; 7 cadaveric knees	36±3.8% (33.18–38.82)	52±3.4% (49.48–54.52)	
Musahl 2003; 8 cadaveric knees			46.2±2.8% (44.26–48.14)
Pietrini 2012; 12 cadaveric knees	36.3±3.8% (34.15–38.45)	51.0±4.0% (48.74–53.26)	
Quantitative Synthesis Mean (95% CI)	35.09% (34.46–35.72)	47.32% (41.69–52.95)	46.2% (44.26–48.14)

All results are in percentages. Quantitative synthesis mean results evaluated by a continuous random effects model using OpenMetaAnalyst software. Results in parentheses are 95% CI

CI confidence interval

^a Calculated standard deviation measurements from similar studies. ±SD

Fig. 6. Amis and Jakob's line quantitative synthesis mean from the combined studies drawn to scale. See Table 2 for specific measurement data.

Fig. 7. Measurement system described by Staubli and Rauschning. Quantitative synthesis mean from the combined studies drawn to scale of radiographic footprint of ACL on tibia. *AM* anteromedial bundle, *PL* posterolateral bundle. See Table 3 for details.

Table 3 Tibial measurements—Staubli method

Staubli measurement technique	Center of the AM bundle, % distance from anterior tibia (95% CI)	Center of the PL bundle, % distance from anterior tibia (95% CI)
Iriuchishma 2010; 15 cadaveric knees	31±3% (29.48–32.52)	50±3% (48.48–51.52)
Zantrop 2008; 20 cadaveric knees	30±3% ^a (28.68–31.32)	44±3% ^a (42.68–45.32)
Quantitative Synthesis Mean (95% CI)	30.43% (29.44–31.42)	46.99% (41.11–52.87)

All results are in percentages. Quantitative synthesis mean results evaluated by a continuous random effects model using OpenMetaAnalyst software. Results in parentheses are 95% CI

CI confidence interval

^aCalculated standard deviation measurements from similar studies. ±SD

measurements to these three systems because they have been used with the most frequency, they provide enough information to localize the center of the footprint on two-dimensional radiographs, and they have been shown to demonstrate excellent interobserver and intraobserver reliability in at least one study.

The Bernard grid method has been studied with the most frequency and cumulatively has the most data available for analysis. The lateral radiograph of the femur utilizing the Bernard grid method provides enough information to

identify the location of the ACL secondary to anatomical constraints of the femoral notch. The AP radiograph of the femur for evaluation of tunnel position is not necessary assuming that finding the medial aspect of the lateral femoral condyle is not a technical challenge of the surgery (as opposed to the lateral aspect of the medial femoral condyle which could appear as the same point on a lateral radiograph). In the past, AP radiographs have been used for tunnel position using a clock-based system. However, the information obtained is superfluous to the lateral radiograph

Table 4 Summary of recommendations

Summary of recommendation

- For further studies, there would be benefit from both single- and double-bundle evaluations of the ACL since reconstruction methods include methods
 - A meticulous synovectomy is imperative in order to evaluate ligament anatomy related to the bony architecture
 - Separation of the ACL into the AM and PL components can be facilitated by observing relative tightness of the two bundles in flexion and extension
 - Utilize radiopaque markers to outline the footprints as well as to calculate the center of the footprints on anatomical studies
- Gold standard measurement systems and current literature consensus
 - All future studies should include interrater and intrarater reliability for individual measurements
 - Current data is limited by the assumption that individual measurements are accurate and precise
 - The quadrant method—the lateral radiograph of the knee with the femoral condyles superimposed is utilized to evaluate ACL anatomy position on the femur
 - Current literature
 - Single bundle
 - 34% from the posterior condyle
 - 33% from Blumensaat's line
 - Double bundle
 - AM
 - 22.75% from the posterior condyle
 - 23.23% from Blumensaat's line
 - PL
 - 32.48% from the posterior condyle
 - 49.96% from Blumensaat's line
 - Amis and Jakob method—the lateral radiograph of the knee with the posterior aspect of the medial and lateral tibial plateau overlapping is utilized to evaluate ACL anatomy position on the tibia
 - Current literature
 - Single bundle
 - No measurements available
 - Double bundle
 - AM 35.09% from anterior
 - PL 47.32% from anterior
 - The AP radiograph of the knee described by Pietrini et al. and Linter et al. with the fibula bisected by the lateral aspect of the tibial plateau, and the measurement taken as a percentage from lateral of the entire tibial plateau
 - Current literature
 - Single bundle
 - 49% (or 51% from the medial edge) from the lateral edge
 - Double bundle
 - AM is 44.2±3.4% from the medial edge
 - PL is 50.1±2.1% from the medial edge

which provides the only two dimensions of relevance (cephalad vs caudad, and anterior vs posterior) secondary to the anatomical shape of the notch (medial vs lateral is not relevant because the tunnel is on the lateral aspect of the medial femoral condyle). In addition, the AP radiograph evaluation method most commonly used is the clock face, which is an arbitrary application of a measurement device to a structure that is not shaped like a clock. It is also very challenging to standardize application of the clock face in a reproducible fashion due to projection variability secondary to knee flexion combined with knee internal or external rotation, as well as the difficulty of standardizing how the clock position is applied to the notch (Is 12 o'clock the top of the notch, or are 3 o'clock and 6 o'clock parallel to the joint line?). Since the Bernard grid method gives the relevant information, we propose that it alone should be used as the gold standard. It is a useful measurement for surgeons to know for a reference in particular because the femur has the fewest intraoperative anatomical reference points aside from the native ACL footprint that may or may not be present depending on the clinical presentation.

Unlike the femur that has anatomical features that constrain possible locations of the tunnel to two dimensions, the tibia requires verification on both the AP and lateral radiograph. The two proposed measurement systems as gold standards include the Amis and Jakob method that evaluates the footprint of the ACL on the lateral radiograph, and the center of the ACL as a percent from medial to lateral on the AP radiograph as described by Pietrini et al. [19]. The AP measurements of the tibia are only found in one additional study [15]. When deciding between the two measurement systems for the lateral radiograph of the tibia, we felt that the Amis and Jakob method [1] was better than the Staubli method [22]. It made more sense to include the Amis and Jakob method as the gold standard because more data is available. In addition, the Staubli method ignores the slope of the tibial plateau by referencing off a line perpendicular to the axis of the tibia that bisects the posterior condyles of the tibial plateau. If a patient has proximal tibial deformity or a high degree of slope, then the radiographic measurement would be skewed. The Amis and Jakob method accounts for this by referencing off the joint line and thus appears to be a better measurement for the gold standard.

While variability of the ACL footprint does exist, its femoral and tibial origins may be estimated based upon standard AP and lateral radiographs. The most commonly employed method for the femoral footprint was the Bernard grid method [3]. The most commonly employed methods for tibial footprint assessment used the lateral radiograph (Amis and Jakob) and the AP radiograph (Lintner et al. and Pietrini et al.). The information presented herein offers surgeons another important tool for accurate ACL footprint identification.

In conclusion, our summation of the data can serve to guide future research efforts in defining the radiographic anatomy of the ACL footprint. We recommend that research should focus on three measurements proposed: the Bernard grid method [3], the lateral radiograph of the tibia described by Amis and Jakob [1], and the AP radiograph measurement

as described by Lintner et al. and Pietrini et al. [15, 19]. Interrater and intrarater reliability studies should be conducted on each measurement system to evaluate reliability. Last, it is essential that the clinician use this data as a supplement to clinical acumen, since “averages” for ACL footprint location may not be applicable to patients that have anatomical variation and further studies need to be performed to identify the variability in radiographic ACL anatomy.

Disclosures

Conflict of Interest: Jaron P. Sullivan, MD, Shane Cook, MD, Yubo Gao, PhD and Brian R. Wolf, MD, MS have declared that they have no conflict of interest.

Human/Animal Rights: This article does not contain any studies with human or animal subjects performed by the any of the authors.

Informed Consent: N/A

Required Author Forms Disclosure forms provided by the authors are available with the online version of this article.

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