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# Size and Shape of the Human Anterior Cruciate Ligament and the Impact of Sex and Skeletal Growth:

## A Systematic Review

**Stephanie G. Cone, BS**[1,2,*], **Danielle Howe, BS**[1,2,*], **Matthew B. Fisher, PhD**[1,2,3]

[1]Joint Department of Biomedical Engineering, North Carolina State University and the University of North Carolina–Chapel Hill, Raleigh, North Carolina

[2]Comparative Medicine Institute, North Carolina State University, Raleigh, North Carolina

[3]Department of Orthopaedics, University of North Carolina–Chapel Hill, Chapel Hill, North Carolina

## Abstract

**Background:** High rates of anterior cruciate ligament (ACL) injury and surgical reconstruction in both skeletally immature and mature populations have led to many studies investigating the size and shape of the healthy ligament. The purposes of the present study were to compile existing quantitative measurements of the geometry of the ACL, its bundles, and its insertion sites and to describe effects of common covariates such as sex and age.

**Methods:** A search of the Web of Science was conducted for studies published from January 1, 1900, to April 11, 2018 describing length, cross-sectional area, volume, orientation, and insertion sites of the ACL. Two reviewers independently screened and reviewed the articles to collect quantitative data for each parameter.

**Results:** Quantitative data were collected from 92 articles in this systematic review. In studies of adults, reports of average ACL length, cross-sectional area, and volume ranged from 26 to 38 mm, 30 to 53 mm$^2$, and 854 to 1,858 mm$^3$, respectively. Reported values were commonly found to vary according to sex and skeletal maturity as well as measurement technique.

**Conclusions:** Although the geometry of the ACL has been described widely in the literature, quantitative measurements can depend on sex, age, and measurement modality, contributing to variability between studies. As such, care must be taken to account for these factors. The present study condenses measurements describing the geometry of the ACL, its individual bundles, and its insertion sites, accounting for common covariates when possible, to provide a resource to the clinical and scientific communities.

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M.B. Fisher: mbfisher@ncsu.edu.

[*] Stephanie G. Cone, BS, and Danielle Howe, BS, contributed equally to this work.

Investigation performed at the Joint Department of Biomedical Engineering, North Carolina State University and the University of North Carolina–Chapel Hill, Raleigh, North Carolina

Appendix
Supporting material provided by the authors is posted with the online version of this article.

**Clinical Relevance:** Quantitative measures of ACL geometry are informative for developing clinical treatments such as ACL reconstruction. Age and sex can impact these parameters.

## Background

The anterior cruciate ligament (ACL) is one of the primary ligaments in the tibiofemoral joint and acts to stabilize the knee under multiple loading conditions, including anterior tibial loads, varus-valgus moments, and internal-external moments[1–5]. In order to resist excess joint motion, the ACL is composed primarily of highly aligned collagen fibers connecting the lateral wall of the femoral intercondylar notch and the anteromedial aspect of the tibial plateau[6–8]. ACL injury leads to knee instability, and, as such, ACL reconstruction (ACLR) procedures are performed at a rate of 250,000 per year[9,10]. These injuries are associated with high rates of early-onset osteoarthritis (even following reconstruction)[11–13] and an increased likelihood of future ACL injury[14,15]. In order to identify risk factors for ACL injury and improve outcomes following ACL injury, a large body of work has been developed to describe the native structure and function of the ACL.

Previous reports on the size and shape of the ACL have included qualitative descriptions and quantitative analysis of the tissue. Specifically, these descriptions have included geometric properties (length, cross-sectional area, and volume), descriptions of the existence and number of ACL bundles, angular orientation, tissue shape, fiber orientation and torsion, and insertion site properties, among other parameters. Many of these parameters have been studied in order to develop anatomical ACLR procedures. For example, ligament cross-sectional area and length can be used to determine graft sizes, angular orientation can inform bone tunnel placement, and multi-bundle ACL descriptions can motivate multi-bundle ACLR procedures. These properties have been assessed with covariates, including sex differences[16,17] and differences between patients with a history of ACL injury and healthy controls[18,19]. Recently, increasing numbers of ACL injuries in young athletes have led to increased interest in age-dependent changes[20–22].

Technological advances over the past 3 decades have led to changes in data-collection modalities and improvements in accuracy. Increased field strength for magnetic resonance imaging (MRI) scanners has led to higher-resolution images, whereas measurements during movement can be assessed with dynamic imaging instead of invasive gauges[23–26]. New scan sequences and relaxometry techniques provide the opportunity to study regional properties within tissues noninvasively[27–29].

At a basic-science level, these parameters can be applied to advance computational modeling of the ACL. Such models can be valuable tools to study mechanisms of injury and function under various loading conditions that are difficult to simulate experimentally. The ability to determine structural measurements (e.g., cross-sectional area) along the ligament, including at the insertion sites, allows the behavior of the ACL and interactions at its boundaries to be more accurately modeled.

To facilitate both clinical and basic-science research, the objectives of the present study are to provide an overview of qualitative descriptions of human ACL morphology and to systematically review the available quantitative values of the size and shape of the human ACL and its insertion sites. When available, the geometric properties of the anteromedial, intermediate, and posterolateral bundles of the ACL will be reported. Sex and age will be identified as covariates when possible. We will also highlight data on the skeletally immature ACL.

## Methods

This review was registered on the PROSPERO international prospective register of systematic reviews (ID: CRD42018096338), where the goals of the review were described and the search and inclusion criteria were defined. The initial registration of this review was approved on June 6, 2018. To summarize qualitative descriptions of the ACL, we referenced both recent and highly cited manuscripts describing ACL morphology found through the Web of Science (Thomson Reuters, Web of Science Core Collection).

To condense quantitative measurements of the ACL, 2 reviewers conducted literature searches through the Web of Science. All searches were date-restricted to January 1, 1900, through April 11, 2018. The search and selection process followed Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) guidelines (Fig. 1)[30]. Studies that included graphic data representation without numerical reports were excluded. For length, a search was performed using key terms “anterior cruciate ligament” AND “length*.” Of the 1,165 reports that were identified, 25 included quantitative data on the length of the human ACL at full knee extension. For cross-sectional area, we used key terms “anterior cruciate ligament” AND “area.” Of the 960 reports that were identified, 21 included quantitative data on the cross-sectional area of the human ACL. For volume, we used key terms “anterior cruciate ligament” AND “volume*.” Of the 463 reports that were identified, 13 included quantitative data on the volume of the human ACL. For the ACL angle, we used key terms “anterior cruciate ligament” AND “angle*” AND “orientation*” OR “inclination*.” Of the 148 reports that were identified, 10 included quantitative data on the ACL angle. For the ACL insertions, we used key terms “anterior cruciate ligament” AND “insertion*” AND “size” OR “area” OR “footprint.” Of the 282 reports that were identified, 23 included quantitative data on human ACL insertion sites.

## Results

### Qualitative Descriptions of the ACL

Decisions regarding how to qualitatively describe ACL geometry inform subsequent quantification of geometric parameters. As such, we will first review these qualitative descriptions before presenting quantitative data.

At the most general level, the ACL has been described as a single structure connecting the tibial and femoral insertions. Although the ACL is more complex, such simplification mimics most ACLR procedures that replace the ACL with a single bundle of graft tissue spanning tunnels in the femur and tibia[31–34]. Such procedures reestablish the primary function of the ACL, although some studies have suggested that this method may fail to replicate full biomechanical function, particularly with regard to rotational stability[35,36].

Other descriptions of the ACL divide the tissue into multiple bundles, frequently defining the ACL as a double-bundle structure. These 2 bundles are classically defined as anteromedial and posterolateral bundles and are often distinguished by a tissue sheath between the bundles and separate locations of the insertion sites[4,37–41]. Functionally, the anteromedial bundle of the ACL is dominant at deeper knee flexion, whereas the posterolateral bundle is engaged near full extension[42]. Additionally, the anteromedial bundle contributes more to ACL function under anterior tibial loads, whereas the posterolateral bundle plays a greater role under rotational loads[43,44]. Double-bundle ACLR procedures attempt to restore the function of both bundles[36,45]. Surgical advantages and disadvantages of these procedures compared with traditional single-bundle ACLR have been well described[45–47].

Some investigators have described the ACL as a triple-bundle structure. In those studies, the bundles most commonly have been defined as anteromedial, intermediate, and posterolateral bundles[48] or as anteromedial-medial, anteromedial-lateral, and posterolateral bundles[49]. The third bundle (i.e., the anteromedial-lateral or intermediate bundle) is situated between the anteromedial (or anteromedial-medial) bundle and the posterolateral bundle. In 1 study, the intermediate bundle was located in approximately 20% of 73 patients (Fig. 2)[48]. Laboratory studies have shown that the intermediate bundle has increased function at 30° and 45° of flexion under anterior drawer testing[50]. Triple-bundle ACL studies have been limited primarily to the laboratory setting and have not become common in the operating room. In 1 clinical study involving 41 patients who underwent a triple-bundle ACLR procedure, anteromedial and intermediate bundles were found to be well preserved with taut graft tension and good synovial coverage at second-look arthroscopy 6 to 22 months after initial ACLR[51]. However, 10% of patients had a complete posterolateral bundle rupture.

Other descriptions of the ACL have avoided bundle-related definitions. Instead, the shape of the ACL has been described as ribbon-like; that is, broad and flat, particularly toward the insertions[52–54]. The midsubstance of the ligament has a rounded or elliptical cross-section, with an oval isthmus and larger insertion areas, so the ACL also has been described as having the shape of an hourglass[55] or a bow tie[56]. These descriptions of a flat ribbon ex vivo and a more rounded structure in vivo are reconciled in the description of the ACL as a ribbon under torsion. The fibers in the ACL twist about the long axis of the ligament, making the ribbon structure appear rounded. These fibers rotate internally from the femoral to the tibial insertion, with reported values ranging from 44° to 84° at 90° of flexion across studies[57,58]. On the basis of MRI measurements, Li et al. reported that the twist angle increased by approximately 30° to 35° from full extension to 90° of flexion[58]. This internal twist may be important for the biomechanical function of the ACL within the knee[59]. In summary, the proper qualitative description of the ACL is still hotly debated, but the various existing descriptions are important for interpreting the following quantitative descriptions.

## Length of ACL

Length is one of the most commonly reported metrics of ACL geometry. Early studies of ACL length involved the use of radiographs[60], Kirschner wires[61], or a digitizer[5] to collect measurements. While methods involving calipers[62–65], 3-dimensional (3D) scanners[16,17], and a digitizer[66] have been used recently, MRI is the most common method as it allows researchers to make noninvasive, in situ measurements[67–79].

Quantitative data on ACL length are presented in Table I. For consistency, all lengths reported in Table I and Appendix Table S1 were made with the knee at full extension. Individual studies showed fairly low variability between subjects. In skeletally mature patients, the mean length of the entire ACL at full extension ranged from 27 to 38 mm[60,67–72,77,80,81]. In many studies, lengths of the individual bundles of the ACL were measured as well, as summarized in Appendix Table S1. In studies with combined male and female data, the anteromedial bundle was longest (average length, 30 to 44 mm), whereas the posterolateral bundle was shortest (average length, 22 to 30 mm)[61,66,70,71,73–75,82]. The intermediate bundle had an average length of 30 to 33 mm[61,71,74].

Quantitative data on ACL length at 0°, 30°, 60°, and 90° of flexion are presented in Appendix Table S2. ACL length is dependent on knee flexion, with the length decreasing from full extension to 90° of flexion in most studies[58,66,67,74,75,80,82]. This finding has obvious implications for graft fixation during ACLR. Notably, 1 study demonstrated an increase in length of the total ACL through flexion[77]. This difference may have been due to measurement method, as Guenoun et al. measured length in 2 dimensions in the sagittal plane[77], whereas other studies involved the use of 3D methods[5,58,61,66–68,70,74,75,80,82]. In terms of the ACL bundles, studies consistently have demonstrated that the posterolateral bundle shortens with flexion[5,61,68,70,74,75,82]. However, there has been less agreement across studies for the anteromedial bundle, with some studies indicating that the anteromedial bundle lengthens with increasing flexion[5,61] and others indicating that it shortens[68,70,75,82].

Sex and age impact ACL length. The ACL has been found to be approximately 4% to 12% shorter in females as compared with males (Table I and Appendix Table S1)[16,17,65,76,78,79]. Additionally, ACL length has been examined across age in young subjects. One study involved the use of light microscopy to measure fetal ACL length, which averaged 3.7 mm at 17 to 23 weeks of gestation[41]. Another study, involving MRI, demonstrated that the average ACL length increased from 24.6 mm at the age of 4 years to 39.2 mm at the age of 18 years (Fig. 3)[83]. ACL length consistently increased until the age of 13 to 15 years, at which point it plateaued. That study also demonstrated that ACL length was similar for males and females until the age of 10 to 12 years, after which ACL length in males was longer by approximately 5 mm.

## Midsubstance Cross-Sectional Area of ACL

The cross-sectional area of the ACL affects tissue stiffness, and cross-sectional area (or, as a proxy, graft diameter) is an important parameter for sizing reconstruction grafts. Cross-sectional area is measured as the area of the ACL on a plane perpendicular to the long axis of the ligament[80]. Quantitative cross-sectional area has been measured with use of a variety of methods, including MRI, 3D scanners, and cameras (Table II)[16,52,54,64,80,84–96]. It also has been calculated from caliper measurements based on the assumption of rectangular[53] or circular[62,97] shapes. In studies with combined male and female data, the average ACL cross-sectional area has ranged from 30 to 53 mm$^2$ in the literature[52–54,62,64,80,85–88,90]. Both intra-study and inter-study variability of cross-sectional area measurements has been greater than that of ACL length measurements. Within studies, standard deviation values have been an average of 24% of the mean reported cross-sectional area values but only 9% of the mean reported length values. Similarly, between studies, reported means have fallen within a range of approximately 50% of the mean cross-sectional area and 30% of the mean length.

In terms of covariates, ACL cross-sectional area in females has been found to be 17% to 39% smaller than that in males[16,91–95,97,98]. Average cross-sectional area typically has been reported to range from 24 to 58 mm$^2$ in females and from 33 to 83 mm$^2$ in males (Table II)[91–95,98]. In 1 study involving 3 groups of skeletally immature females with average ages of 9.7, 12.9, and 14.8 years, the average ACL cross-sectional area was 26, 29, and 27 mm$^2$, respectively[99]. Furthermore, that study demonstrated that ACL cross-sectional area normalized to body weight and height decreased with age, from 0.007 to 0.003 cm$^2$/kg-m.

## Volume of ACL

ACL volume has been reported less commonly than ACL length and cross-sectional area. ACL volume has been most often measured through segmentation and reconstruction from sequential MRI scans[16,17,64,100]. Quantitative measurements of ACL volume are summarized in Appendix Table S3. Average ACL volume as measured with MRI has been reported to range from 854 to 1,858 mm$^3$ in the literature[64,91,101–103]. This roughly 1,000-mm$^3$ range in reported mean values indicates high variability in ACL volume across studies. Additionally, the reported standard deviations within studies were 25% to 38% of the means. As volume measurements often require image processing, factors such as variability among users, software differences, and smoothing algorithms likely affect these differences. One study evaluated the volumes of the anteromedial and posterolateral bundles separately and demonstrated that these bundles comprised approximately 45% and 55% of the total ACL volume, respectively[104].

On the average, ACL volume in females has been found to be 10% to 35% smaller than that in males (Appendix Table S3). Comparisons of ACL volume between right and left knees have revealed no significant side-to-side differences[105]. Tuca et al. reported that average ACL volume increased throughout skeletal growth, from approximately 300 cm$^3$ in patients aged 3 to 7 years to approximately 1,300 cm$^3$ at skeletal maturity[20]. Interestingly, volume plateaued at 10 years of age.

## Angular Orientation of ACL

The angular orientation of the ACL is important because alterations in orientation can result in changes in joint stability, tissue force levels, and distributions under loading. Graft orientation is an important variable in ACLR. Commonly reported angles include coronal and sagittal plane angles relative to the tibial plateau and the angle between the ACL and the Blumensaat line.

Quantitative values for ACL orientation are summarized in Appendix Table S4. As these parameters are sensitive to knee flexion, the values reported here were measured at full extension. The sagittal plane angle of the ACL has been reported to range from approximately 45° to approximately 65° in skeletally mature patients[58,63,77,81,106–108]. Fewer studies have evaluated the coronal angle[63,81,106,107], with mean values ranging from approximately 65° to approximately 78°. Typical values for the angle between the ACL and the Blumensaat line have ranged from 7° to 13° on average[63,77,108]; however, alternative calculation methods have provided lower values[106,109].

In a study of the impact of sex on ACL orientation, no significant differences were found between skeletally mature males and females in the sagittal or coronal planes (Appendix Table S4)[110]. Similarly, in a study on the impact of sex and skeletal maturity on ACL orientation, sex was not found to significantly impact the sagittal or coronal ACL angles or the angle between the ACL and the Blumensaat line in subjects with open or closed physes[22]. In contrast, age was found to have a significant effect on sagittal and coronal ACL angles in skeletally immature subjects. Kim et al.[22] and Reid et al.[21] found that the sagittal and coronal ACL angles increased by approximately 20° from birth through maturity (Fig. 4[22]).

## Insertion Site Morphology of ACL

The size of the femoral and tibial insertion sites of the ACL has been described according to many parameters, including length and width, cross-sectional area, and the ratio of major and minor diameters[52,80,96]. In the present discussion, we focus on studies in which cross-sectional area has been used to describe the sizes of the insertion sites. Many techniques, including MRI, computed tomography (CT) scans, intraoperative measurements, laser scans, photographs, and caliper measurements, have been used to assess ACL insertion sites.

The cross-sectional area of the femoral ACL insertion site most frequently has been reported to range from 60 to 130 $mm^2$ (Table III)[38,80,96–98,111–121]. Higher values, on the order of 190 $mm^2$, have been reported in some studies[122,123]. The high variability across studies may represent natural anatomical variation, inclusion or exclusion of the fan-like fibers extending from the ligament, altered sensitivity between scan sequences, or varied measurement precision. In terms of individual bundles, the cross-sectional area of the femoral insertion site of the anteromedial bundle has been reported to range from 35 to 65 $mm^2$, whereas the cross-sectional area of the femoral insertion site of the posterolateral bundle has been reported to range from 32 to 66 $mm^2$ (Appendix Table S5)[37,39,111,116,124].

In terms of sex, 1 study demonstrated no significant difference between male and female subjects in terms of the overall femoral insertion cross-sectional area[98], whereas another study found that the individual cross-sectional area values for both the anteromedial and posterolateral bundles were approximately 25% larger for males than for females[38]. Another study demonstrated no significant side-to-side differences within individuals in terms of the femoral ACL insertion site[96].

The tibial insertion of the ACL also has been extensively characterized. Reported average values for tibial insertion cross-sectional area have generally ranged from approximately 100 to 160 square millimeters[39,85,87,97,113,114,117,118,120,122,125] while a few studies have demonstrated mean values closer to 180 square millimeters[80,126]. For the anteromedial bundle, the tibial insertion cross-sectional area has generally ranged from 60 to 70 square millimeters[37,39,124], although 1 study demonstrated a mean value of 98 square millimeters[126]. For the posterolateral bundle, the tibial insertion site cross-sectional area has ranged from 50 to 75 square millimeters[37,39,124,126]. One study demonstrated that the tibial insertion site was approximately 10% larger in males than in females[38,39]; however, another study demonstrated no significant difference[124]. Similar to the femoral insertion of the ACL, the cross-sectional area of the tibial insertion was not found to vary between right and left knees[96].

While cross-sectional area is a valuable tool for describing insertion site size, the shape of the ACL insertion site is far more complex than a single number can encompass. Guenther et al., in a study of 100 patients, divided the tibial insertion of the ACL into 3 shape classifications (elliptical, triangular, and “C”-shaped) and reported frequencies of 51%, 33%, and 16%, respectively (Fig. 5)[127]. This type of classification points toward the potential need for individualized clinical approaches based on patient anatomy, although the ultimate functional impact of these different shapes has not been fully determined. Along with differences in ACL insertion footprint shape, the anatomy of the enthesis, including the fan-like fibers extending from the primary ligament, also varies. Previous studies analyzing the microanatomy of the ACL enthesis have evaluated parameters such as the enthesis insertion angle, the enthesis width and length, and the relative areas of calcified or uncalcified fibrocartilage[128], but much work remains to determine the clinical importance of these parameters.

## Discussion

The present systematic review summarized the available literature on the size and shape of the human ACL. Qualitative descriptions of the morphology of the ACL were first presented. Then, quantitative measurements of ACL length, cross-sectional area, volume, angular orientation, and insertion areas were condensed from the existing literature. The impact of covariates such as sex, age, side (right/left), and measurement modality was also detailed. Such data can be used by clinicians and researchers to better understand the native ACL, to identify risk factors associated with injury, and to design better treatments to improve patient outcomes after injury.

Comparison between sexes is increasingly common, often revealing clinically important and statistically significant differences. Overall, the size of the ACL and surrounding anatomy tend to be larger in males compared with females. For example, length[16,17,65,76,78,79], cross-sectional area[16,91–95,97,98], and volume[16,17,19,100,104,129,130] have been found to be larger in males. Differences due to sex may be confounded by other variables such as height and weight, both of which have been shown to correlate positively with ACL size[16,95,104]. However, Anderson et al. found that ACL area normalized to total body mass remained ~15% larger in males than in females[95]. Comparisons in ACL structure between left and right knees also have been reported[96,105]. Few, if any, statistical differences have been found. However, in athletes, it may be more relevant to report data between dominant and nondominant limbs as the impact of limb dominance on ACL behavior is not clear[131].

Furthermore, recent increases in ACL injuries in children and adolescents have led to heightened interest in age-specific treatment options[132]. Currently, the long-term outcomes of these procedures are often poor, with high rates of second and third ACL injuries, osteoarthritis, and meniscal lesions[133,134]. In order to improve ACLR procedures in these age groups, many recent studies have aimed to increase our understanding of the structure and function of the ACL during growth. In childhood and adolescence, many anatomical parameters undergo more complex changes than simply scaling with body size. The angular orientation of the ACL steepens in both the sagittal and coronal planes with increasing age[21,22]. Studies have identified age-dependent relationships between ACL cross-sectional area and other metrics of growth such as individual muscle cross-sectional area and body size, suggesting age-specific relationships between the size of the ACL and the size of other tissues[20,99]. Given that all of these changes could impact ACL function, consideration of growth and maturation may be key to developing improved solutions for pediatric ACL injuries.

Geometric measures of the ACL are relevant to graft selection, but these data are also relevant in the field of computational modeling. Models can be used to predict functional behavior of native tissues[135–138] and outcomes of surgical procedures that cannot be easily tested in vivo[79,137,139,140]. The desires to develop robust models and move toward personalized medicine are driving improvements in the collection, analysis, and reporting of structural and functional properties of tissues including the ACL. Some groups have begun to incorporate more accurate geometries into finite-element models of the ACL by incorporating a double-bundle structure[141], hourglass geometries with realistic torsion and fiber orientation[142], or subject-specific geometries from MRI scans[138,143], incorporating fiber orientation captured through digitization[144]. Ultimately, more detailed reporting of the structure and properties of the native ACL will result in more accurate and detailed models.

In summary, the present report aggregates information from previous studies that have qualitatively and quantitatively characterized the size and shape of the ACL. Specific parameters of interest include tissue length and cross-sectional area as well as regionally dependent geometries, such as the individual bundles and the insertions into bone. Variations due to sex and age are increasingly being reported across studies and may lead to a more accurate understanding of ACL size and shape.

## Supplementary Material

Refer to Web version on PubMed Central for supplementary material.

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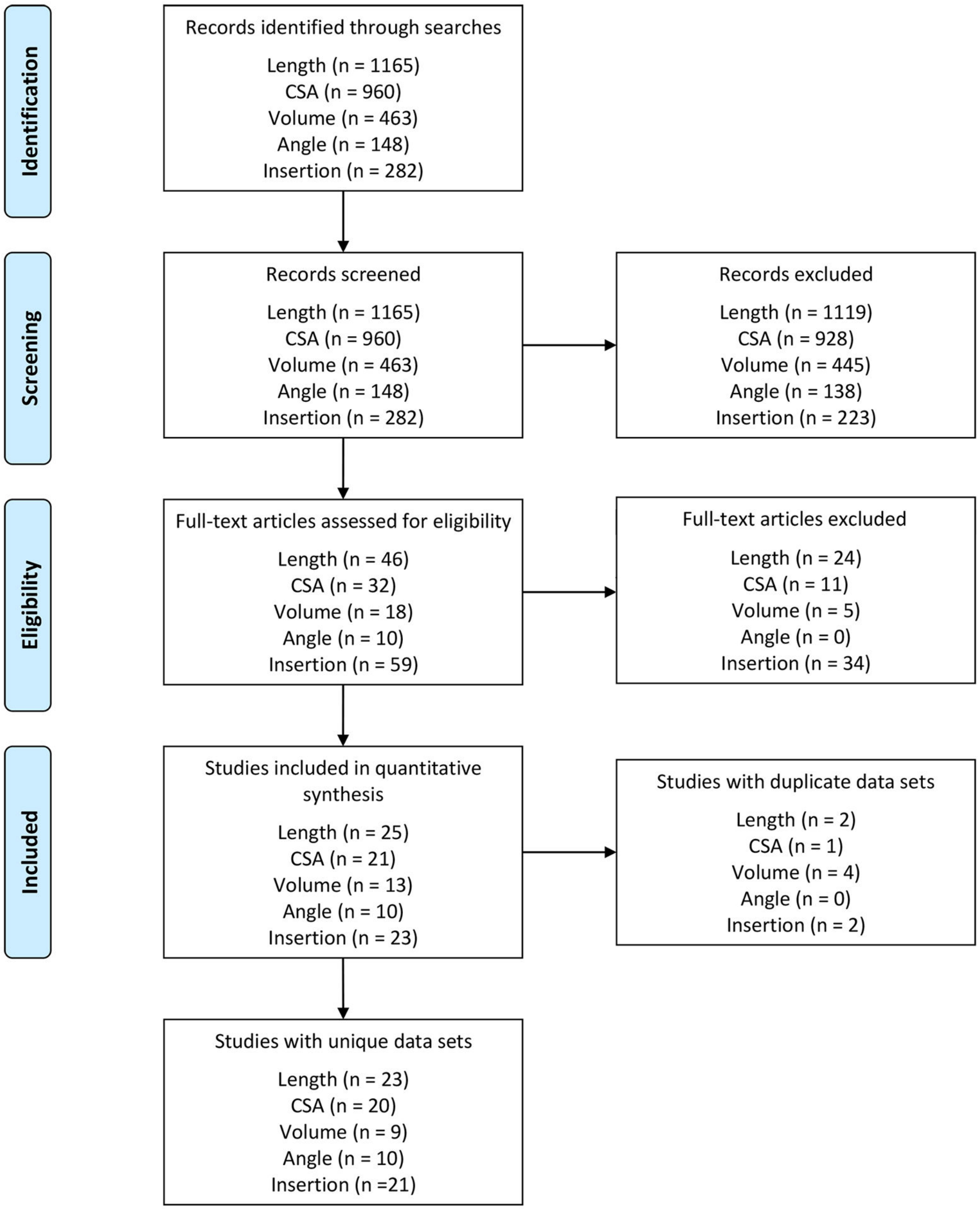

**Fig. 1.**

PRISMA flow diagram for study inclusion, showing the number of studies associated with the 5 separate searches that were performed (length, cross-sectional area [CSA], volume, angle, and insertion).

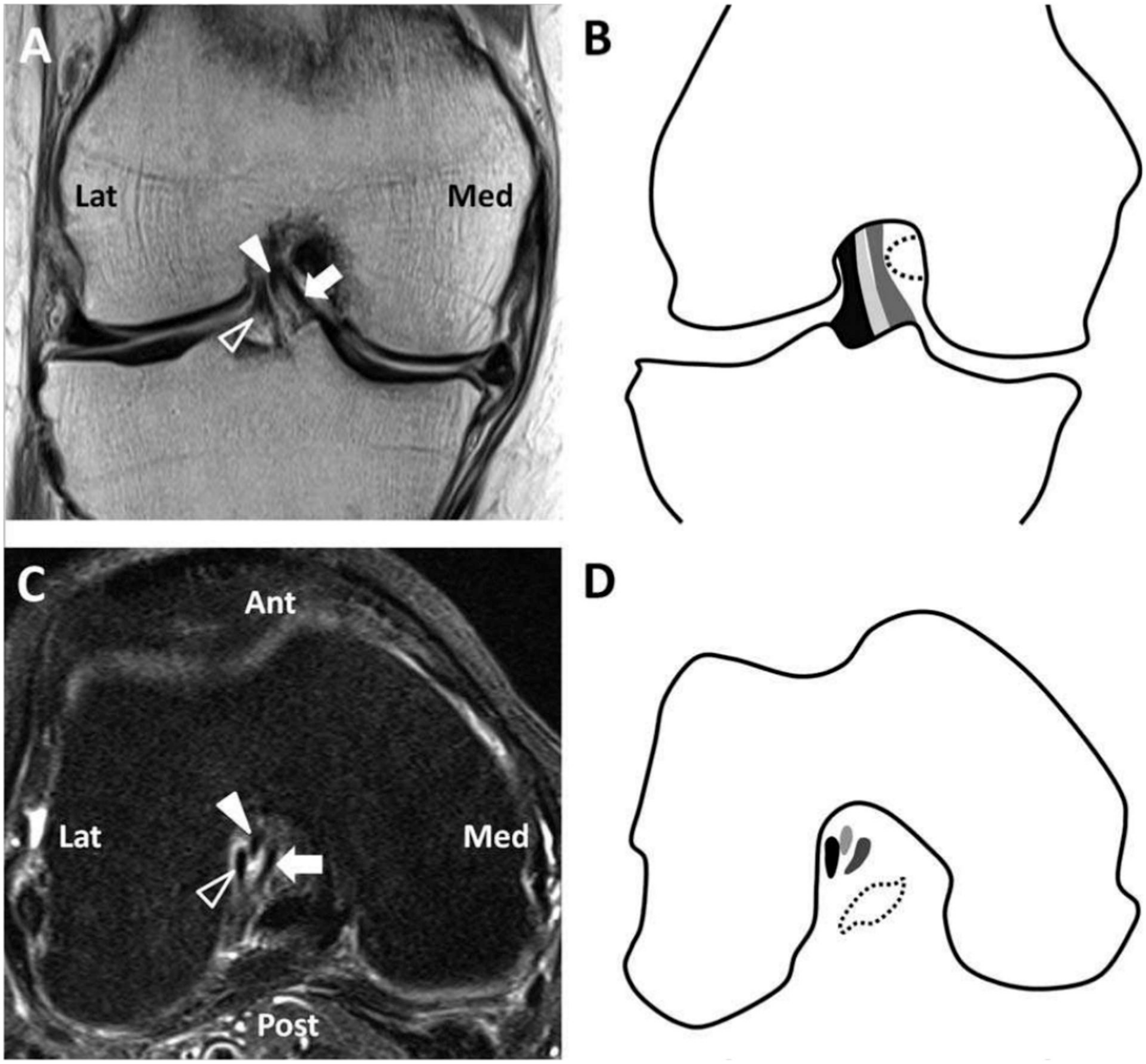

**Fig. 2.**

Proton-density (Figs. 2-A) and T2-weighted fat-saturated (Figs. 2-C) MRI scans and 2-dimensional renderings (Figs. 2-B and 2-D) showing the division of the ACL into anteromedial, intermediate, and posterolateral bundles. (Reproduced, with permission from John Wiley and Sons, from: MacKay JW, Whitehead H, Toms AP. Radiological evidence for the triple bundle anterior cruciate ligament. Clin Anat. 2014 Oct;27[7]:1097–102. Epub 2014 Jun 3https://www.ncbi.nlm.nih.gov/entrez/query.fcgi?cmd=Retrieve&db=PubMed&list_uids=24890455&dopt=Abstract. © 2014 Wiley Periodicals, Inc.)

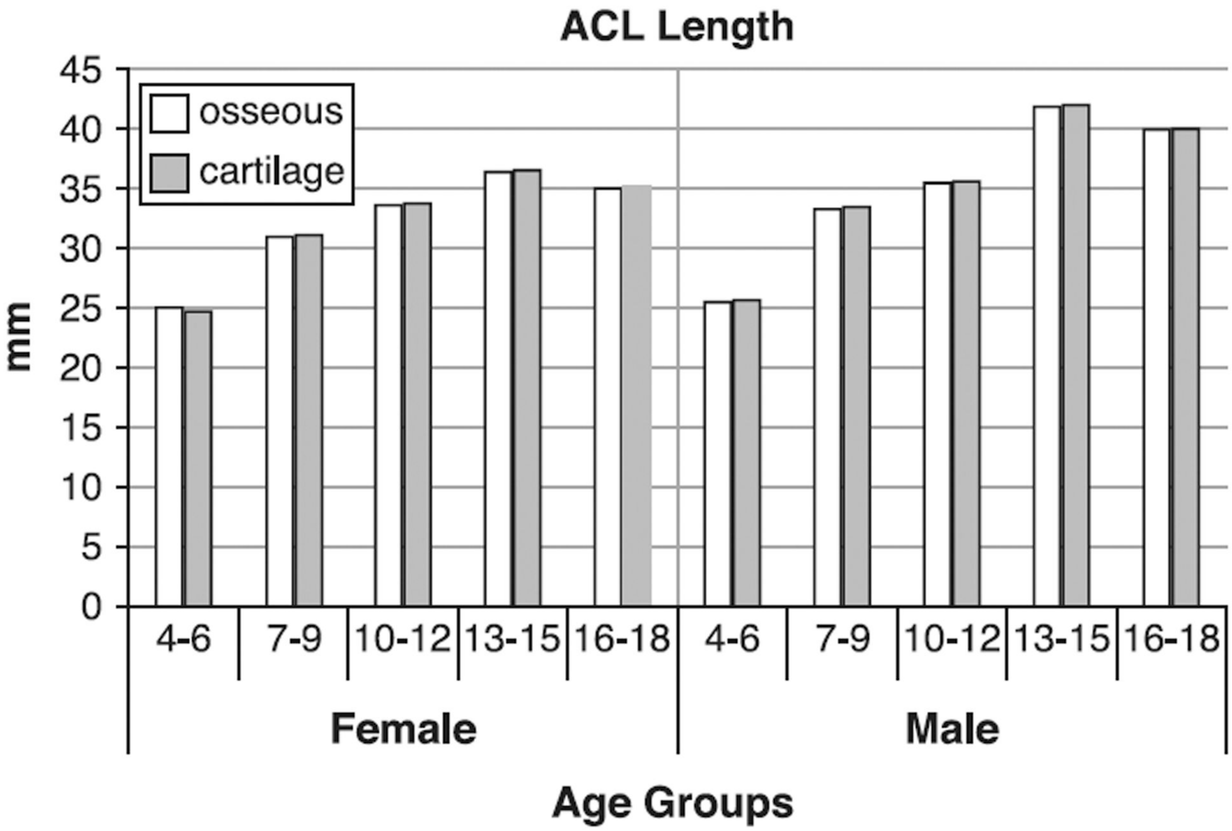

**Fig. 3.**

Bar graph showing ACL length according to age for males and females as reported by Edmonds et al.[83]. That study included 68 female patients and 64 male patients, with 9 to 18 subjects per age group. ACL length increased with age from 4 years to approximately 13 to 15 years and differed between males and females in the adolescent age groups. (Reproduced, with permission from Wolters Kluwer Health, from: Edmonds EW, Bathen M, Bastrom TP. Normal parameters of the skeletally immature knee: developmental changes on magnetic resonance imaging. J Pediatr Orthop. 2015 Oct-Nov;35[7]:712–20https://www.ncbi.nlm.nih.gov/entrez/query.fcgi?cmd=Retrieve&db=PubMed&list_uids=25494026&dopt=Abstract. https://journals.lww.com/pedorthopaedics/pages/default.aspx)

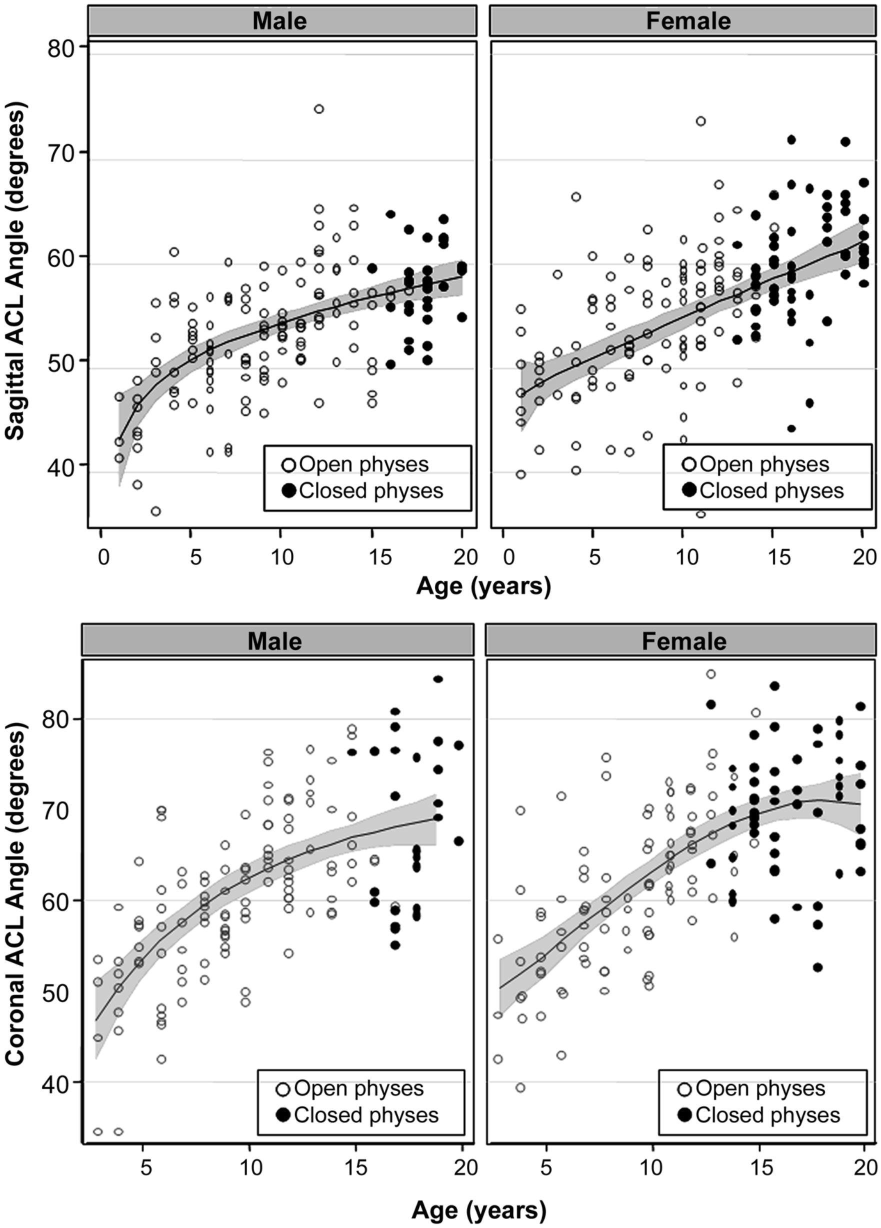

**Fig. 4.**

Scatterplots with polynomial regression curves and 95% confidence intervals showing that the sagittal and coronal ACL angles increased significantly from birth through late adolescence in both males and females in the study by Kim et al.[22]. (Reproduced, with permission from the Radiological Society of North America [RSNA], from: Kim HK, Laor T, Shire NJ, Bean JA, Dardzinski BJ. Anterior and posterior cruciate ligaments at different patient ages: MR imaging findings. Radiology. 2008 Jun;247[3]:826–35https://www.ncbi.nlm.nih.gov/entrez/query.fcgi?cmd=Retrieve&db=PubMed&list_uids=18487537&dopt=Abstract.)

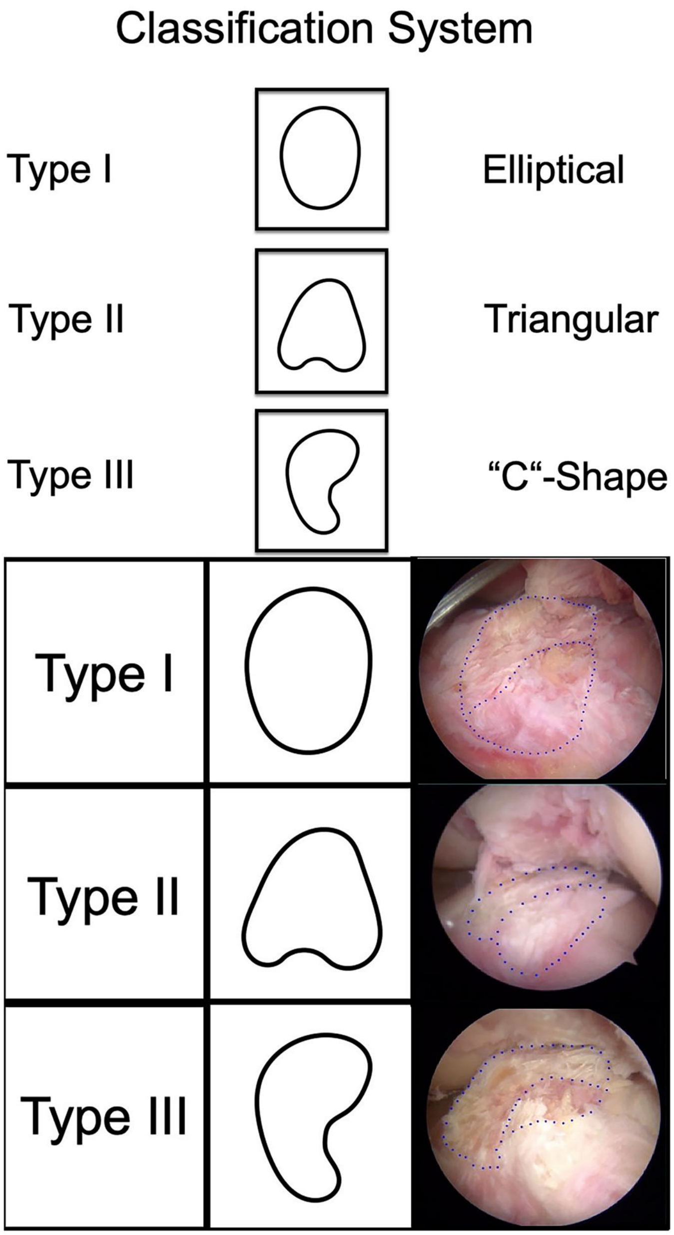

**Fig. 5.**

Classification of ACL tibial insertion sites as elliptical, triangular, and “C”-shaped as assessed intraoperatively. (Adapted, with permission from Springer Nature, from: Guenther D, Irarrázaval S, Nishizawa Y, Vernacchia C, Thorhauer E, Musahl V, Irrgang JJ, Fu FH. Variation in the shape of the tibial insertion site of the anterior cruciate ligament: classification is required. Knee Surg Sports Traumatol Arthrosc. 2017 Aug; 25[8]:2428–32. Epub 2015 Dec 12. © 2017 Springer Nature. https://link.springer.com/journal/167.)

## TABLE I

ACL Length

| **Study** | **ACL Length[*]** ***(mm)*** | **No. of Knees** | **Male:Female Ratio** ***(no. of patients)*** | **Age[†]** ***(yr)*** | **Acquisition Method[‡]** |
|---|---|---|---|---|---|
| Guenoun et al.[77] (2017) | 32.5 ± 2.6 | 20 | 9:11 | 32 (24–47) | 1T open MRI (STIR, T2 fat sat) (in vivo) |
| Fujimaki et al.[80] (2016) | 31.1 ± 3.1 | 8 | 8:0 | 57.5 ± 8.0 | Laser scanner (ex vivo) |
| Taylor et al.[67] (2013) | 34.5 ± 1.4[§] | 8 | 7:1 | 26 (22–32) | 3T MRI (DESS) and fluoroscopy (in vivo) |
| Utturkar et al.[68] (2013) | 30.2 ± 2.6 | 8 | 8:0 | 30 ± 7 | 3T MRI (DESS) and fluoroscopy (in vivo) |
| Abebe et al.[81] (2011) | 27.0 ± 3.0 | 22 | 16:6 | NR (19–49) | 3T MRI (DESS) and fluoroscopy (in vivo) |
| Hosseini et al.[69] (2009) | 27.1 ± 2.3 | 9 | 4:5 | NR (23–48) | 3T MRI (in vivo) |
| Hashemi et al.[64] (2005) | 29.4 ± 4.7 (22.2–36.5) | 15[#] | — | — | Calipers (ex vivo) |
| Li et al.[70] (2004) | 30.1 ± 3.8 | 5 | — | 25 ± 5 | 1.5T MRI (FIESTA) and fluoroscopy (in vivo) |
| Boisgard et al.[71] (1999) | 34.2 | 1 | — | — | 1T MRI (T1) (in vivo) |
| Högerle et al.[72] (1998) | 38.2 ± 3.4 (30–45) | 50 | 39:11 | 34 | 1.5T MRI (in vivo) |
| Miller and Dandy[60] (1991) | 36.7 ± 2.2 (31–41) | 100[#] | 48:36 | 32 (16–58) | Radiograph (in vivo) |
| Wang et al.[78] (2013), Wang et al.[79] (2015) | | | | | 1.5T MRI (in vivo) |
| Male | 37.0 ± 4.1 | 158[#] | 79:0 | NR (15–71) | |
| Female | 35.8 ± 4.7 | 156[#] | 0:78 | NR (15–73) | |
| Stijak et al.[65] (2009) | | | | | Calipers (ex vivo) |
| Male | 31.9 ± 2.7 | 32 | 32:0 | 37 ± 10 | |
| Female | 28.1 ± 3.1 | 18 | 0:18 | 28 ± 10 | |
| Chandrashekar et al.[16] (2005), Hashemi et al.[17] (2011) | | | | | 3D scanner (ex vivo) |
| Male | 29.8 ± 2.5 | 10 | 10:0 | 39 (26–50) | |
| Female | 26.9 ± 2.8 | 10 | 0:10 | 37.7 (17–50) | |
| Takai et al.[5] (1993) | | | | | Digitizer (ex vivo) |
| Anterior | 30.6 ± 1.3 | 8 | — | 36 (23–46) | |
| Posterior | 26.0 ± 0.8 | 8 | — | 36 (23–46) | |

[*] The values are given as the mean and the standard deviation (with or without the range in parentheses), with the knee at full extension, unless otherwise noted.

[†] The values are given as the mean and the standard deviation or as the mean with the range in parentheses. NR = not reported.

[‡] MRI sequences include STIR (short T1 inversion recovery), T2 fat sat (T2 fat saturation), DESS (double echo steady state), and FIESTA (fast imaging employing steady state acquisition) sequences.

[§] The values are given as the mean and the 95% confidence interval.

[#] Some knees were paired.

## TABLE II

ACL Cross-Sectional Area

| Study | ACL Cross-Sectional Area[*] *(mm$^2$)* | No. of Knees | Male:Female Ratio *(no. of patients)* | Age[*] *(yr)* | Acquisition Method[†] |
|---|---|---|---|---|---|
| Thein et al.[54] (2016), Bowers et al.[84] (2011) | 49.3 ± 13.9 (25.8–93.4) | 30 | 14:16 | 24 (16–38) | 3T MRI (in vivo) |
| Lee et al.[85] (2016) | 47.2 ± 13.4 (22.0–83.0) | 92 | 72:20 | 34.7 (20–60) | 3T MRI (in vivo) |
| Fujimaki et al.[80] (2016) | 39.9 ± 13.7 | 8 | 8:0 | 57.5 ± 8.0 | Laser scanner (ex vivo) |
| Siebold et al.[52] (2015) | 38.7 ± 7.7 (20.3–51.5) | 20 | 7:10 (3 not available) | 78 (62–108) | Digital camera and calipers (ex vivo) |
| Śmigielski et al.[53] (2015) | 39.8 | 111[‡] | 45:36 | 67 (32–74) | Digital calipers (ex vivo) |
| Vermesan et al.[86] (2015) | 31.7 ± 2.1 | 12 | 9:3 | — | 1.5T MRI (T2) (in vivo) |
| Cavaignac et al.[62] (2014) | 30.7 ± 7.0 (21.2–44.2) | 16 | 4:16 (4 excluded) | 84 (77–90) | Calipers (ex vivo) |
| Iriuchishima et al.[87] (2014) | 46.9 ± 18.3 | 12 | 4:8 | 86.3 ± 8.1 | Digital camera (ex vivo) |
| Grzelak et al.[88] (2012) | 40.6 (23.8–59.1) | 19 | 19:0 | 26.6 ± 5.3 | 1.5T MRI (T1) (in vivo) |
| Hashemi et al.[64] (2005) | 52.6 ± 16.3 | 15 | — | — | Photographic 3D scanner (ex vivo) |
| Whitney et al.[91] (2014) | | | | | 3T MRI (T1, PD) (in vivo) |
| Male | 47 ± 11 | 27 | 27:0 | 18.0 ± 2.5 | |
| Female | 39 ± 11 | 61 | 0:61 | 17.1 ± 2.2 | |
| Pujol et al.[97] (2013) | | | | 76 (64–93) | Calculated from circumference measured by suture (ex vivo) |
| Male | 33.2 | 10[‡] | 5:0 | — | |
| Female | 25.5 | 12[‡] | 0:6 | — | |
| Lipps et al.[93] (2013) | | | | 53 ± 7 | 3T MRI (T2) (ex vivo) |
| Male | 35.5 ± 11.2 | 10[‡] | 5:0 | — | |
| Female | 31.4 ± 8.7 | 10[‡] | 0:5 | — | |
| Lipps et al.[92] (2012) | | | | | 3T MRI (PD, T2) (ex vivo) |
| Male | 39.6 ± 11.7 | 9 | 9:0 | 60.8 ± 17.2 | |
| Female | 24.2 ± 8.4 | 9 | 0:9 | 65.7 ± 18.4 | |
| Dienst et al.[94] (2007) | | | | | 1.5T MRI (T2) (in vivo) |
| Male | 68.4 ± 20 | 10 | 10:0 | 26.2 ± 2 | |
| Female | 45.2 ± 10 | 10 | 0:10 | 24.4 ± 2 | |
| Chandrashekar et al.[16] (2005) | | | | | Photographic 3D scanner (ex vivo) |
| Male | 83.5 ± 24.9 | 10 | 10:0 | 39 (26–50) | |
| Female | 58.3 ± 15.3 | 10 | 0:10 | 37.7 (17–50) | |
| Anderson et al.[95] (2001) | | | | | 1.5T MRI (PD) (in vivo) |
| Male | 48.9 | 100[‡] | 50:0 | 16.1 | |

| **Study** | **ACL Cross-Sectional Area[*] *(mm$^2$)*** | **No. of Knees** | **Male:Female Ratio *(no. of patients)*** | **Age[*] *(yr)*** | **Acquisition Method[†]** |
|---|---|---|---|---|---|
| Female | 36.1 | 100[‡] | 0:50 | 16.2 | |
| Muneta et al.[98] (1997) | | | | | Measurements from negative mold (ex vivo) |
| Male | 46.7 ± 7.7 | 8 | 8:0 | 77 ± 11 | |
| Female | 37.0 ± 9.7 | 8 | 0:8 | 72 ± 12 | |
| Dargel et al.[96] (2009) | | | | | Digital images (ex vivo) |
| Right | 50.9 ± 15.5 | 20 | 8:12 | 71 (62–86) | |
| Left | 44.5 ± 11.6 | 20 | 8:12 | 71 (62–86) | |
| Triantafyllidi et al.[90] (2013) | | | | | Digital microscope camera (ex vivo) |
| Superior midsubstance | 35.4 ± 2.5 | 8 | 4:4 | 59 (50–70) | |
| Inferior midsubstance | 39.4 ± 2.2 | 8 | 4:4 | 59 (50–70) | |

[*] The values are given as mean and the standard deviation, with the range in parentheses, when data were available.

[†] MRI sequences include the PD (proton density) sequence.

[‡] Some knees were paired.

## TABLE III

ACL Insertion Site Cross-Sectional Area

| | **Cross-Sectional Area*** ***(mm$^2$)*** | | | | | |
|---|---|---|---|---|---|---|
| **Study** | **Femoral Insertion Site** | **Tibial Insertion Site** | **No. of Knees** | **Male:Female Ratio** ***(no. of patients)*** | **Age*** ***(yr)*** | **Acquisition Method†** |
| Tampere et al.[122] (2017) | 194.5 ± 38.3 | 159.2 ± 31.3 | 8 | 4:4 | 81.5 (66–97) | CT (ex vivo) |
| Lee et al.[85] (2016) | 60.3 ± 12.5 (34–98) | 96.8 ± 22.1 (57–150) | 92 | 72:20 | 34.7 (20–60) | 3T MRI (in vivo) |
| Fujimaki et al.[80] (2016) | 122.1 ± 30.2 | 175.8 ± 64.3 | 8 | 8:0 | 57.5 ± 8.0 | Laser scanner (ex vivo) |
| Iriuchishima et al.[113] (2015) | 69.8 ± 25 | 133.8 ± 31.3 | 26 | 10:16 | Median, 84.5 (68–98) | Digital camera (ex vivo) |
| Iriuchishima et al.[114] (2015), Iriuchishima et al.[87] (2014) | 72.3 ± 24.4 | 134.1 ± 32.4 | 24 | 9:15 | Median, 84 (68–98) | Digital camera (ex vivo) |
| Pujol et al.[97] (2013) | 96.8 (80–121) | 117.9 (90–130) | 22‡ | 5:6 | 76 (64–93) | Manual measurement (ex vivo) |
| Swami et al.[120] (2013) | NA (71–87) | NA (95–113) | 37 | 15:22 | 15.8 ± 0.2 | 1.5T MRI (PD, T2) (in vivo) |
| Iriuchishima et al.[117] (2013) | 84.0 ± 25.3 | 144.7 ± 35.9 | 18 | 7:11 | Median, 83 (68–97) | Digital camera (ex vivo) |
| Iriuchishima et al.[118] (2013) | 85.4 ± 26.3 | 145.4 ± 39.8 | 14 | 5:9 | 79.3 ± 8.2 | Digital camera (ex vivo) |
| Suruga et al.[111] (2017) | 125 ± 47 | — | 23 | 7:16 | Median, 83 (69–96) | Digital photograph (ex vivo) |
| Iriuchishima et al.[116] (2016) | 102 (72–199) | — | 14 | 6:8 | Median, 82.5 (69–96) | Digital camera (ex vivo) |
| Iwahashi et al.[121] (2010) | 128.3 ± 10.5 (113.6–137.5) | — | 8* | 3:1 | 77 (66–87) | Calipers (ex vivo) |
| Ferretti et al.[123] (2007) | 196.8 ± 23.1 (158.1–230.4) | — | 16‡ | 4:4 | 75 (57–94) | Laser scanner (ex vivo) |
| Tashiro et al.[126] (2018) | — | 182.7 ± 41.1 | 50 | 33:17 | 21.4 ± 6.8 | 3T MRI (DESS) (in vivo) |
| Siebold et al.[52] (2015) | — | 110.9 ± 14.7 (80.1–133.1) | 20 | 7:10 (3 NA) | 78 (62–108) | Calipers (ex vivo) |
| Guenther et al.[125] (2017) | | | | | | Intraoperative and 1.5T MRI (T2, PD) (in vivo) |
| Intraoperative | — | 123.8 ± 21.5 (61.3–172.8) | 117 | 68:49 | 24.4 ± 9.1 | |
| MRI- user 1 | — | 132.8 ± 15.7 (75.1–188.5) | 117 | 68:49 | 24.4 ± 9.1 | |
| MRI- user 2 | — | 136.7 ± 15.4 (71.7–184.5) | 117 | 68:49 | 24.4 ± 9.1 | |
| Muneta et al.[98] (1997) | | | | | | Measurements from negative molds (ex vivo) |
| Male | 99.6 ± 25.0 | 155.0 ± 32.2 | 8 | 8:0 | 77 ± 11 | |
| Female | 86.9 ± 42.2 | 131.7 ± 28.1 | 8 | 0:8 | 72 ± 12 | |

| | **Cross-Sectional Area[*] *(mm²)*** | | | | | |
|---|---|---|---|---|---|---|
| **Study** | **Femoral Insertion Site** | **Tibial Insertion Site** | **No. of Knees** | **Male:Female Ratio *(no. of patients)*** | **Age[*] *(yr)*** | **Acquisition Method[†]** |
| Siebold et al.[38] (2008),<br>Siebold et al.[39] (2008) | | | | | 82 (61–100) | Digital camera (ex vivo) |
| Male | 98 ± 22 | 130 ± 45 | 17[‡] | 9:0 | | |
| Female | 76 ± 13 | 106 ± 29 | 33[‡] | 0:18 | | |
| Dargel et al.[96] (2009) | | | | | | Digital camera (ex vivo) |
| Right | 122.3 ± 27.2 | 140.3 ± 20.1 | 20 | 8:12 | 71 (62–86) | |
| Left | 119.5 ± 29.8 | 137.4 ± 28.0 | 20 | 8:12 | 71 (62–86) | |

[*] The values are given as mean and the standard deviation, with the range in parentheses, when data were available, unless otherwise noted. NA = not available.

[†] MRI sequences included PD (proton density) and DESS (double echo steady state) sequences.

[‡] Some knees were paired.