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MORPHOMETRY OF ANTERIOR CRUCIATE LIGAMENT

Jahira Banu[1], Yogesh Ashok Sontakke[2]*, Dharmaraj Tamgire[3]

[1.]Junior Resident, [2,3]Associate Professor,

*[*1,2,3]Department of Anatomy, Jawaharlal institute of Postgraduate Medical Education and Research (JIPMER), (An Institution of National Importance under the Ministry of Health & Family Welfare, Govt. of India), Pondicherry, 605006 India.*

Corresponding author:

Email: dryogeshas@rediffmail.com

Abstract: -

Anterior cruciate ligament (ACL) is one of the ligaments in the complex knee joint. ACL is connecting the two bony structures maintaining the knee joint stability in anteroposterior direction. Stability of the joint can be disturbed in case of injuries to the knee joint. Surgeries in replacing the ligament are the best option for treating knee ligament injury. Graft replacement needed an appropriate size. Different parameters such as ACL length, width, cross sectional area, insertional area is borne to be in mind for preparation and proceeding the ACL surgery. Various parameters on morphometry of ACL are reviewed in this article. Studies of morphometry from cadaver and living subjects are included in the review. This article may give an idea about the parametric measurement of ACL and will guide the surgeons for the treatment of ACL injuries.

Key words: *Cruciate ligament, morphometry, ligament grafting*

INTRODUCTION

The anterior cruciate ligament (ACL) is an intra-articular ligament of knee joint plays a vital role in maintaining the anteroposterior stability. It runs from the anterior intercondylar area of the tibia to the posteromedial aspect of the femur. Functionally the Anterior cruciate ligament (ACL) is described to have two or three bundles, named as anteromedial (AM) and a posterolateral bundle (PL), intermediate based on the attachments over the tibia.[1-9] Anteromedial bundle attachment on femur lies anterosuperiorly when compared with the posteroinferior attachment of posterolateral bundle. Tibial attachment site for anteromedial bundle lies anteromedially and posterolaterally for the posterolateral bundle.[10] The primary action of ACL is to prevent anterior displacement of tibia off from the femur. Bundles of ACL act differently with different movements of knee joint. [11] Anteromedial bundle restrains better in 45^0 of flexion and posterolateral bundle in full flexion. [12]

Anterior cruciate ligament tears are common because of the increased sports and recreational activities with incidence of 68.6 per 100,000 person-years. [14] The mechanisms involved in the injury of ACL is sudden rotatory movements with the foot planted firmly or may also occur due to hyperextension of knee joint. [15] The common treatment approach for ACL injury surgical correction with the placement of graft. As ACL functionally is said to have two or three bundles, replacement surgeries should replace the functions of native ACL. For functional replacement of ACL, bundle replacement procedure was followed which includes single bundle or double bundles. Grafts were harvested from the hamstrings or patellar tendon as allograft or autograft. Malpositioned grafts lead to complications like reconstruction failures, secondary osteoarthritis, meniscal injuries.[18-19] To avoid complications following replacement surgery anatomical knowledge of native ACL is more important to choose an appropriate graft with the correct size and for a successful outcome. One of the main cause for the treatment failure is technical error including inappropriate calculation of the size of the graft.[20] Therefore, knowledge of the morphometry of ACL is more important. Studies have calculated the morphometry of ACL by different methods using cadavers, healthy volunteers and even in post reconstructed patients to find the morphology of ACL. Parameters such as length, width of entire ACL and bundles of ACL, cross-sectional area, insertion site measurements include length, width and area are more needed for the graft preparation. This review includes collection of variable measurements approach on ACL with application of different methods are posted. Findings on measurement will guide the surgeons for the treatment of ACL surgeries.

MATERIALS AND METHOD

Search engine: PubMed. For writing review on ACL morphometry, PubMed is used as a search engine. Key word used are morphometry, anterior cruciate ligament and anatomy. Inclusion criteria: Articles included in this review were related to the parameters on length, width, cross-sectional and insertion areas and no of bundles on ACL in mm/cm. Articles in the english language were only included. Exclusion criteria: Studies involving animal studies, structures other than ACL and articles other than the english language were excluded.

REVIEW

Reviewed morphometry of ACL

In the present article, the reviewed parameters included length, width, cross-sectional area, thickness, tibial and femoral insertional area, number of bundles and tibial and femoral insertional area of each bundle of ACL. The length and width of ACL was studies by using different methods of measurement in various studies. The average length of ACL ranges from 30.35 to 36.88 mm (Table 1). The average width of the ACL ranges from 5.9 to 16 mm for ACL (Table 2). Most of the studies have shown that ACL has two bundles (ranges from 1-3 bundles). The bundles are named as anteromedial and posterolateral. The width of the anteromedial bundle ranges from 4.2 to 8.5 mm, whereas posterolateral bundle ranges from 3.7 to 7.7 mm (Table 2). The cross-sectional area of ACL ranges from 29.7 to 83.54 mm^2 (Table 3), whereas the thickness of ACL ranges from 3.3 to 4.96 mm (Table 4). The tibial and femoral insertional area of ACL was measured by different methods in various studies. Total tibial insertional surface area of ACL ranges from 114 mm to 182.7 mm^2. The length of the tibial insertional area of ACL ranges from 13. 4 mm to 20 mm, whereas its width ranges from 7.3 mm to 13.5 mm (Table 5). Total femoral insertional surface area of ACL ranges from 29.1 mm^2 to 196 mm^2. The length of the tibial insertional area of ACL ranges from 12.9 mm to 18.3 mm, whereas its width ranges from 4.3 mm to 10.4 mm (Table 6).

Reviewed morphometry of Bundles of ACL

Most of the author agreed on the presence of two bundles in ACL as anteromedial and posterolateral. Some of the author showed presence of third (intermediate bundle) in the substance of the ACL (Table 7). The tibial and femoral insertional area of ACL was measured by different methods in various studies. Total tibial insertional surface area of anteromedial bundle of ACL ranges from 56 mm^2 to 136mm^2. The length of the tibial insertional area of anteromedial bundle of ACL ranges from 8.9 mm to 14.6 mm, whereas its width ranges from 5 mm to 9.8 mm (Table 8). Total tibial insertional surface area of posterolateral bundle of ACL ranges from 52 mm^2 to 93 mm^2. The length of the tibial insertional area of posterolateral bundle of ACL ranges from 7.4 mm to 14.9 mm, whereas its width ranges from 4 mm to 8 mm (Table 8). Total femoral insertional surface area of anteromedial bundle of ACL ranges from 44 mm^2 to 120 mm^2. The length of the tibial insertional area of anteromedial bundle of ACL ranges from 7 mm to 12.2 mm, whereas its width ranges from 4.7 mm to 8.9 mm (Table 8). Total tibial insertional surface area of posterolateral bundle of ACL ranges from 40 mm^2 to 103mm^2. The length of the tibial insertional area of posterolateral bundle of ACL ranges from 6 mm to 11 mm, whereas its width ranges from 4.7 mm to 7. 6 mm (Table 9).

DISCUSSION

ACL ligament plays an important function in maintaining anteroposterior stability of knee joint. As it prone to injuries due to various sports activities its morphometric analysis plays an important role in the field of orthopaedics to construct the graft in accordance with correct measurements. Researchers used various modalities of measurement using different study groups for finding the different parameters. The parameters discussed in this study include number of bundles, length of ACL, width of ACL, and insertional areas over tibia and femur.

Methods for measurement of various parameters

Most of the researchers have used Vernier calipers, MRI, 3D scanned photograph, biplanar fluoroscopy, radiograph 3T Trio Scanner, high resolution computed tomography (HRCT), micrometre, electromagnetic system/3D system, 3D/3S space Fastrak electromagnetic tracking system, X-ray image processing software, circular disc, arthroscopic bendable ruler, measuring scale, contrast CT /3D Scanning, computer image mapping software, CT scan/Bone surface model, laser 3D digitalized camera and MR imaging system, photoshop software, radiographs with grid method, 3D Model photograph/software ImageJ software for measuring morphometric parameters of ACL. The Vernier caliper is most commonly used measuring instrument.

Length of ACL

Intrarticular length of ACL also plays a crucial role for better stability of the knee joint. More length of ACL will lead to increased movement and impingement of grafts, length less than the normal values will lead to loss of maintaining the anteroposterior stability. The length of the ACL fibers varies as knee undergo various degrees of motion. [29, 31, 34, 36] For calculation of length of ACL, authors have used variable measurement methods with cadaver and living subjects. By reviewing length parameters, we found out that ACL measurement was considered as single bundle. [2,22,23,24,26,34] Few authors reported the length of ACL as individual bundles. [2, 27, 29] Additionally, the length of an ACL also predicted from the various movements of the knee joint [28, 30, 33, 35], gender-wise [25, 29] and by side wise [32] by different methods. Most common methods applied for length measurement are use of measuring device or Mituitiyo Vernier caliper with cadaver as subjects. Zyl RV studied the maximum cadavers (91 cadavers). [2, 23, 25, 26, 31, 33, 34] MRI measurements of length of ACL was also used but with healthy subjects. Boisgard S, et al. used MRI with different movements of Knee joint and reconstructed the movements as 3D model. They noticed that the anteromedial bundle was longer by 30% compared with the other two bundles. [22] Cohen SB, et al. outlined the bundles of ACL in patients with MRI and compared with the arthroscopic values. They also found out that the length of AM was longer than the PL bundle. [27] Wang HP, et al. used MRI compared length of ACL between left and right sides and between genders. They arrived the values of right and left side ACL more or less equal and male value is more than the female. [38] Yoo YS, et al. calculated the length of ACL by using reference points and created four virtual bundles. They scanned the ACL with CT scan and converted it is a 3D Model and measured with a customized software (Rapid form 2006 basis INUS, Inc., Korea). The length of the bundles was measured at the different knee flexion angles (0^0, 45^0, 90^0 and 135^0). They observed that all bundles achieved increased in length at extension. They suggested that position for knee graft tensioning and fixation to be in full extension. [28] Taylor K, et al. studied the relative strain in the ACL during the stance and swing phases on normal levels of walking. They created in vivo models with help of magnetic resonance imaging, biplanar fluoroscopy, and motion capture. They chose normal walking movements to measure knee flexion, ACL length, and relative ACL strain during gait. They concluded that the length of the ACL was decreased as flexion angle increased both in stance as well as in swing phases. [30]

Fujimaki Y, et al. used eight cadaveric knees and MRI/Siemens 3T-Trio scanner as a mode of measurement for evaluating the ACL length. For manipulating the knee joint a Robot CASPAR Staubli RX90 (Ortho MAQUET) was used. They observed in different loading conditions and found that ACL length decreased with the flexion angle. The ACL was longest at 0^0 with ATT and shortest at the 90^0 unloaded position. The average length increased significantly relative to the unloaded position for both ATT and combined rotational load conditions in the extension position. [33]

Width of ACL

Width of an ACL plays an important role in preventing the knee laxity. Studies found that anterior knee laxity has been reported as a risk factor for ACL injury. Lesser width of ACL was considered to cause more Anterior knee laxity. [37] Calculation of width was marked from the cadavers as well as study subjects. Standard methods for cadaveric measurement was calculated with standard micrometre and Vernier caliper. Yelicharla AKR, et al. discovered the minimal variations in width of ACL by gender wise. [31]

Thickness of ACL

Along with other measurable parameters, few authors measured the thickness of ACL. The study subject used were cadaver and patients but different methods of measurements. Highest study subjects were 111 cadavers with Vernier caliper by Smilegski R, et al., the thickness was measured at three different levels of ACL. [39] deOliveria VM, et al. done a study to find the relationship between ACL thickness with anthropometry. They concluded that ACL thickness of ACL depend upon the size of the lateral femoral condyle and there was no relationship between anthropometry and ACL. [40]

Cross-Sectional Area of ACL Midsubstance

Another parameter important for graft preparation is cross sectional area of ACL. Thin ligament may rupture easily. The cross-sectional area of ACL is not same for the entire ACL length. It is increased from femur to tibia and narrow in the centre. Previously ACL injury was reconstructed by using four strands in grafts [42], followed by five, six [43,44] strands. Eight folded grafts were also tried to improve the functional stability of patients. [45] Assessment of cross sectional of ACL was mostly studied with cadaveric based subjects by various methods. Hashemi J, et al. found an alternative method for measuring the anthropometry of anterior cruciate ligament through 3D digital image reconstruction. Commercially available photographic scanner, 3D scan top was used to construct the 3D image of human ACL. The measured areas at the midpoint of the ACL using the 3D scan technique were compared with the micrometer, caliper and digital photography methods. They concluded that compared to other complicated and custom-made equipment, commercially available setup gave accurate results. [46] Chandrashekar N, et al. indicated the increase in anterior cruciate ligament size in proportion to notch width in men but not in women and showed smaller length, cross-sectional area, volume, and mass in women. [25] Iriuichishima T, et al. compared the cross-sectional area of native midsubstance with different grafts used for reconstructions. ImageJ Software was used for comparison of sectional area. [49] The semitendinosus tendon graft measured larger than the ACL cross-sectional area. Fujimaki Y, et al. in 2015, evidenced the CSA at the isthmus represents less than half the area of the insertion sites. [32]

Numbers of bundles

ACL was previously considered as a single structure with one bundle of ligament. [21] Later, with different techniques like MRI and direct blunt dissection, the researchers observed ACL consists of two bundles with different orientation of fibre arrangement act differently in various range of movements. Bundles are named as anteromedial and posterolateral bundle and
intermediate bundle. [1-6,7-9, 9,22]

Insertional Areas of ACL and its Bundle

An insertional area of ACL is important in creating tunnel position for ACL graft. Measurements of femoral and tibial ACL attachments are useful in creating apertures for tunnel creation in replacing graft. Literature abouth tibial insertions of ACL is available more compared with femoral insertion. Replacement surgeries with graft will proceed from tibia towards the femur side. Most of the authors calculated the area of ACL as a single bundle and some calculated it as bundles separately. Study participants observed in the studies under the review are predominantly cadavers followed by patients. Measurement tool more commonly employed is Vernier calipers. With the use of Vernier calipers, attachment site was measured as the anteroposterior and transverse diameter or short axis and long axis or width and length of insertion sites. [26, 29, 31, 39, 51–57] Staubli, et al. measured only the length of the tibial insertional area with a micrometer. [59] Harner CD, et al. determined the size of cruciate ligament insertion sites first, then digitized the insertional areas and acquired the 2D shapes of insertion site areas. A device called electromagnetic system was used for measuring the insertional areas. They denoted the values ACL, AM, PL bundles separately and found that the tibial and femoral insertions areas were approximately 3.5 times larger for ACL compared to the mid-substance of ACL. [60] Cuomo P, et al. studied the width and length of ACL by taking a photograph of insertional areas. [61] Colombet P, et al. used metallic marker beads for defining anatomic points and measured with Vernier caliper, compared with plain radiographs of the specimens. For anatomical measurements, used Vernier calipers for physical measurements and showed that radiographic and physical morphometric findings were similar and no significant changes have been seen. [55] Dargel J, et al. precisely marked the footprints of ACL with a radiopaque barium sulphate emulsion and repeatedly circled with the tip of a scalpel for clear radiographic contrast. After marking X-rays were taken and digitalized. The outer contour of the right and left cruciate ligament insertion was marked digitally in different colors and the corresponding left specimen image was mirrored and overlapped with the images of both sides. The conclusion of his study was the footprints of the cruciate ligament insertions in left and right knees do not show significant congruency, but rather differ considerably with respect to the center of gravity of the cruciate ligament footprint. [62] Takahashi M, et al. divided the ACL into the AMB and PLB at the insertion footprint and marked with an ink pen around the periphery of the bundles. Photograph of femur and tibia specimens were taken with a measuring scale and the photographs were uploaded to a personal computer. The measurements and analysis of the surface of the bundles of ACL were performed using MacSCOPE software. [63] Heming J, et al. while doing a study on anatomical limitations of transtibial drilling in ACL reconstructions measured the insertional areas with sharp point caliper. [53] Luites W, et al. applied an anterior load in 90^0 of flexion to the ACL for producing tension. They identified the anteromedial and posterolateral bundle by using tension pattern in the fibres. Attachment area of AMB and PLB was identified and marked with water-proof felt pen. The attachment areas measured by using 3Space Fastrak electromagnetic tracking system for taking 3D measurements. [1] Steckel H, et al. examined six cadaveric knees to evaluate the double bundle structure of ACL, dynamic motion characteristics and the relationship of knee flexion and relative position of the femoral insertion sites of the ACL. They observed the motion pattern of the AM and PL bundle using a testing machine, AM bundle showed tightening with knee flexion of 90^0 and PL bundle showed tightening with knee extension and with internal rotation when in 90^0 flexion. After these steps he marked the femoral and tibial attachment areas with a pen. Individual bundle length and width were measured using a standard micrometer. The AM and PL insertion sites on the femoral and tibial attachments were measured using digital photographs. [2] Ferretti M, et al. dissected the knees to expose ACL bundles and distinguished the bundles of ACL by observing their tension pattern during a range of knee motion. They marked the femoral attachment of ACL bundles by bluntly dissecting the bundles with a marker pen and the knees were photographed by a laser 3D digitizer camera (Konica Minolta VIVID 910 3D digitizer). They converted a photograph into the 3D model by using the software. The measurements of the length and cross-section areas of the femoral AM and PL bundles, the area of the ACL femoral attachment, and the length of osseous landmarks were noted from the software. [64]

Edward A, et al. used thirty-two disarticulated and twenty-three articulated specimens with intact ACL for measuring the tibial attachment sites of ACL. In disarticulated specimens, identified ACL two fiber bundles when holding in tissue forceps. Then, separated the fiber bundles proximally and created separation plane bluntly in tibial attachment side. In articulated specimens, based on the fiber orientation, pattern and tensioning pattern identified the bundles of ACL and bluntly dissected the bundles in tibial attachment site. After identifying the bundles of ACL in all specimens he excised the bundles from its attachments site. Then, the peripheries of bundle attachment were marked with pen or fine osteotome and high-resolution scaled digital photographs were taken from each dissected specimen. The ACL bundle attachments were obtained by using computer graphics. [66] Edward A, et al. also studied using twenty-two knees for measurement of femoral attachment of ACL and identified the bundles of ACL with the tension pattern and its orientation of fibers. Attachment areas are marked with ink and photographs were taken and a computer graphics program were used to outline the bundle attachment sites. [65] Seibold R, et al. studied the tibial and femoral attachment of ACL bundles. They excised the bundles of ACL near the level of attachment site after identifying the bundles based on their orientation and separated by using probe. The attachment areas were marked with different colored inks. Bundles of ACL over attachment site were marked with different colored inks and photographed with digital camera. Morphometric measurements were made by uploading photographs to image analysis system (computer assisted). They found that insertion area of ACL over tibia was smaller in females. [50] Tallay A, et al. collected resected tibial plateaus from the patients who underwent total knee replacement. After dissection of ACL from its attachment site, insertion footprint was outlined and measurements were made with vernier calipers and photographed with computerized image mapping software (Adobe Illustrator CS3 Mac OSX). [67] Purnell ML, et al. after injecting air intra-articularly of about 15 cc^3 took highresolution computerized axial tomography (CT) and constructed 3-dimensional (3D) model. With the use of volume-rendering software program GE Clear tender program, he studied the bony anatomy of the medial wall of the lateral femoral condyle and the tibial plateau to correlate these measurements with the origin and insertion of the ACL. [68]

Iwahasi T, et al. used eight cadaveric knees for measuring femoral footprints. They captured 3D VR images from CT scan of lateral femoral condyle including ACL attachments. After dissecting the lateral femoral condyle along with the ACL, he subjected the tissue for histological examination and obtained images from the histological study. Correlation of histologic analysis and 3D VR images are been made with these two procedures. For image analysis, CT data were processed with software and the femoral contour was extracted and the 3D bone surface model was created by marching cube technique. Reconstructed images were viewed by use of a modified version of the Visualization ToolKit (VTK) software (Kitware, Clifton Park, NY). Specifically, CT images of the lateral femoral condyle along the obliqueaxial planes parallel to the roof of the notch, identical to the sections for histologic analysis. [69] Kopf S, et al. done a study to evaluate, the in-vivo size variability of the ACL insertion sites and its bundles during arthroscopy. He selected patients undergoing ACLR and identified the ACL, its bundle insertion sites during arthroscopy in a large series of patients and correlate with physical characteristics of the individual. The margins of bundle insertion were identified and marked with electrocautery and measurement taken with the help of an arthroscopic ruler. [70] Pujol N, et al. conducted a study on anatomy of the anterior cruciate ligament related to hamstring tendon grafts by cadavers. He dissected the ACL and harvested the grafts. Insertion sites are stained and he measured length, width and area from both insertional areas. He measured the length as major axis and width as perpendicular to major axis, by considering insertion area as ellipses. (Manual measurements) [71] Otsubo H, et al. used seven fresh frozen knees for defining the attachment and fibre bundles of ACL. They divided the ACL into three bundles using a blunt instrument. After detaching the bundles from attachment sites, he marked the attachment areas with different colours. The images of the ACL attachment were taken from the tibial and femoral sites using a digital camera. Measurement of the insertion areas are calculated using Image J software. [72] Iriuchishima T, et al. while comparing the size of commonly used autografts and the size of the native ACL mid-substance measured the ACL footprints. After dissecting the ACL from its attachment site, ACL was dissected out. The attachment areas was marked with coloured ink and marked area was photographed using digital camera (a Casio EXILIM S12). The measurements were recorded using Image J software. [49]

Triantafyllidi E, et al. while doing a study on ACL to identify the shape and thickness along its length in relation to the PCL together measured the attachments of ACL. By using eight cadaveric specimens, they prepared gross sections and embedded the interconylar notch with paraffin, fixing the cruciate ligaments in neutral positions and removed en bloc. They identified the ligaments geometry and photographed by using Leica DFC425/DFC425C LED Illumination, Trinocular Tube, SmartTouch, and PC System with Leica LAS Software; Leica Microsystems and measurement were taken with the help of Image J software. [41] Ichiba A, et al. studied the tibial attachments of ACL with the help of MRI and compared with physical characteristics of patients. He observed the tibial insertion area in the sagittal view by using MRI. He measured the antero-posterior diameter of ACL. [73] Widhalm HK, et al. studied the tibial insertion area of ACL by correlating the attachments areas preoperatively by MRI and while doing arthroscopy from the patients who undergoing primary ACL reconstruction. A preoperative measurement of ACL tibial insertion area was measured using MRI by two raters. Intraoperative measurement of tibial insertion was taken by specialized ruler. He concluded that the preoperative measuremnts of the tibial attachments by using MRI can act as a valuable aid in preoperative planning of dimensions of knee structures. [74] Guenther D, et al. determined the distribution of different sizes of the area of the tibial insertion site and correlated the preoperative measurements by using MRI with the arthroscopic measurement. They concluded that tibial insertion site varies in size and shape and preoperative measurement of insertion site enables preoperative planning of graft choice and size to optimally cover the tibial insertion site. [75] Tampere T, et al. used eight embalmed cadavers to study the ACL anatomy by using 3D CT technology. After dissection of the knee joint, the ACL was injected with a contrast for CT imaging. The images obtained from the CT scan were imported into Mimics 14.11® software (Materialise

N.V., Heverlee, Belgium) for conversion of 2D (CT) images into 3D reconstructions. Measurements were noted by constructing the native ACL as cylinder from 3D model. [76] Araki D, et al. has done a study to prove that three dimensional isotropic magnetic resonance imaging can provide a reliable estimate of the native anterior cruciate ligament insertion site anatomy. He compared the ACL measurements from MRI with Laser scanner. After outlining the insertion site of ACL from twelve fresh cadavers, isotropic 3D DESS MRI was taken. A boundary of ACL was digitized by using a high accuracy laser scanner. Both the values were compared and he reported that MRI can provide estimates of ACL insertion site area with clinically applicable accuracy. [77] Tashiro Y, et al. has done a study to clarify the morphology of ACL tibial insertion sites, he took ACL- Reconstructed patients as study participants. They constructed 3D models from the MRI images to measure the ACL attachments areas. [78] Lee KJ, et al. compared the anatomy of ACL insertion sites using three different modes of Measurements. He used plain radiography, threedimensional computed tomographic imaging and anatomic dissection. Lengths of the long and short axis, area and centre position of each bundle insertion site were measured. They found that plain radiograph and 3D CT measurements showed a reliable correlation with anatomic measurements and concluded that plain radiograph can be used as a postoperative tool after ACL reconstruction. [79]

SUMMARY AND CONCLUSION

Anterior cruciate ligament (ACL) plays a vital role in the stability of the knee joint. Success of the ACL surgeries is hidden in its complex morphometric structural arrangement. The present article focus on summarizing the observation of reviewed literature and the summary of the reviewed morphometry of ACL and its bundles are listed in Table 10. This compiled data may give insight to the surgeon for treatment various injuries of ACL and getting better postoperative outcomes.

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Table 1: Length of anterior cruciate ligament

No.	Authors	Year	Type of study	No of knees studied	Method of measurement	ACL length (mm)
1.	Clement B, et al. 23	1989	Cadaver	30	Measuring device/Mituitiyo Vernier caliper	30.35 ± 4.10
2.	Tan JL, et al.[24]	1998	Cadaver	30	Vernier calliper	34 ± 3.8
3.	Boisgard S, et al.22	1999	Healthy volunteers	Not mentioned	3D Reconstructed models from MRI	34.2
4.	Chandrashekar N, et al.[25]	2005	Cadaver	20k	Vernier calliper/3D scanner photograph	29.82 ± 2.51(M) 26.85 ± 2.82 (F)
5.	Steckel H, et al.47	2007	Cadaver	12	Standard Micrometre	AM: 37.7 PL: 20.7
6.	Stijak L, et al.[26]	2009	Cadaver	100	sliding Vernier callipers	31.9 ± 2.7
7.	Cohen SB, et al.27	2009	Pateints	162	1.5 Tesla MRI	AM: 36.9 ± 2 .8 PL: 20.5 ± 2.4
8.	Yoo YS, et al. [28]	2010	Healthy volunteers	20	HRCT/3D images/software	Extension: AM-AM: 38.4 ± 0.18 PL-PL: 29.2 ± 0.10 AMOP: 36.4 ± 0.24
9.	Ahmed MAAS. 29	2013	Cadaver	56	Digital calliper	AM:32 ± 3.5mm PL: 23 ± 3mm
10.	Taylor KA, et al. 30	2013	Subjects	16	MRI/Biplanar fluoroscopy/Motion Capture	34.5± 1.4(E) 33.8 ±3.2 (Swing phase)
11.	Yelicharla AKR, et al.[31]	2014	Cadaver	72	Vernier Calliper	43.5 ± 4.1(M) 41.9 ± 3.9(F)
12.	Wang HP, et al.32	2015	Healthy volunteers	314	MRI	36.40 ± 4.44(L) 36.88 ± 4.45(R)
13.	Fujimaki Y, et al.33	2015	Cadaver	16	Radiograph/ MRI/Siemens 3T Trio scanner	(0) 31.1 ± 3.1; (90) 24.3 ± 3.2
14.	Zyl RV, et al.[34]	2016	Cadaver	182	Mechanical dial calliper	32.44
15.	Guenoun D, et al.35	2016	Volunteers	40	MRI	32.5 ± 2.6 (N) 31.75 ± 2.5 (H) 33.55 ±1.8 (45F) 35.6 ±1.6 (90F)
Range of length of anterior cruciate ligament						30.35–36.88

ACL: Anterior cruciate ligament. AM-OP: Anteromedial bundle to over-the-top position. N: Neutral, H: Hyperextension, F: Flexion. M: Male, F: Female. R: Right, L: Left, AM-AM: anteromedial to anteromedial legth in extension, PL-PL: posterolateral to posterolateral length in extension

Table 2: Width of anterior cruciate ligament

No.	Authors	Year	Type of study	No of knees studied	Method of measurement	ACL width (mm)	
1	Steckel H, et al.47	2007	Cadaver	12	Standard Micrometre	AM: 8.5 PL: 7.7	
2	Stijak L, et al. 26	2009	Cadaver	100	sliding Vernier callipers	12.2 ± 1.5	
3	Cohen SB, et al.27	2009	Pateints	162	1.5 Tesla MRI	AM:4.2 ± 0.8 PL:3.7 ± 0.8	
4	Triantafyllidi E, et al.[41]	2013	Cadaver	8	Photograph/Image J program	MS 1 – 7.41 MS 2 – 7.94	
5	Yelicharla AKR. 31	2014	Cadaver	72	Vernier Calliper	12.1 ± 2.4(M) 11 ±1.8(F)	
6	Wang HM, et al. [32]	2016	Recreational women	40	MRI	5.9 ± 1.4	
7	Smilegski R, et al. [39]	2016	Cadaver	111	Vernier calliper	2mm from FI	16
						Midsubstance	11.4
Range of width of the ACL						5.9 to 16 mm	
Range of width of anteromedial bundle						4.2 to 8.5 mm	
Range of width of posteromedial bundle						3.7 to 7.7 mm	

ACL: Anterior Cruciate ligament. M: Male, F: Female

Table3: Cross-sectional area of ACL

No	Authors	Year	Type of study	No of knees studied	Method of measurement	ACL crosssectional area (mm^2) Midsubstance (mm)
1	Muneta T, et al.52	1997	Cadaver	16	Vernier caliper	41.9 ± 9.8
2	Chandrashekar N, et al.[25]	2005	Cadaver	20	3D Reconstruction/Software	83.54 ± 24.89 (M) 58.29 ± 15.32 (F)
3	Hashemi J, et al.46	2005	Cadaver	15	(The 3-D scan top imaging system.)	52.61±16.27
					Micrometre	41.78 ± 14.5
					Vernier caliper	43.67 ±13.82
					photograph	55.89
4	Steckel H, et al.47	2007	Cadaver	12	Standard micrometre	AM :20.3 PL:17.7
5	Bush CJ, et al. 48	2012	Cadaver	44	MR scan	29.7 ± 8.7
6	Iriuichishima T, et al. [49]	2012	Cadaver	12	Image J software	46.9 ± 18.3
7	Pujol N, et al. 71	2012	Cadaver	22	Manual Measurement	29.2
8	Triantafyllidi E, et al.[41]	2013	Cadaver	8	Photograph/Image J program	35.4 39.4
9	Fujimaki Y, et al. 33	2015	Cadaver	16	Radiograph/ MRI/Siemens 3T Trio scanner	43.9 ± 12.1 39.9 ± 13.7
10	Seibold R, et al.50	2015	Cadaver	20	Calipers/digital photograph	38.7
11	Smigielski R, et al.[39]	2015	Cadaver	111	Caliper	39.8
Range of cross-sectional area of the ACL						29.7 to 83.54 mm^2

ACL: Anterior cruciate ligament. **M:** Male**, F:** Female

Table 4: Thickness of ACL

No.	Authors	Year	Type of study	No of sample	Method of measurement	ACL Thickness (mm)
1	Triantafyllidi E, et al.[41]	2013	Cadaver	16	Photograph/Image J program	4.78 (0.59) (MS-1) 4.96 (0.57) (MS-2)
2	De oliveria VM, et al.[40]	2016	Patients	96	MRI	4.5(M-AP); 4.3 (M-FP)
3	Smilegski R, et al.[39]	2016	Cadaver	111	Vernier calipers	2 mm from FI: 3.54 Midsubstance: 3.4 Tibial insertion: 3.3
Range of Thickness of the ACL					3.3 to 4.96mm	

ACL: Anterior Cruciate Ligament. MS: Midsubstance, FI: Femoral insertion

Table 5: Tibial insertion area of ACL

N o	Authors	Yea r	Type of study	No of samp le	Method of measurement	Tibial insertion of ACL		
						Width (mm)	Length (mm)	Surfac e area (mm^2)
1	Staubli HU, et al. 59	1994	Cadaver	10	Micrometer	-	15 ± 3.2	
2	Muneta T, et al. [52]	1997	Cadaver	16	Micrometer	-	-	143.4
3	Tan JL, et al. 24	1998	Cadaver	30	Vernier calipers	9.7 ± 3.4	13.1 ± 4.4	
4	Harner CD, et al. 60	1999	Cadaver	10	Electromagnetic system/ 3D sytem			136 ±33
5	Cuomo P, et al. [61]	2006	Cadaver	21	Photograph/ software	9 ± 2	17 ± 2	
6	Colombet P, et al. [55]	2006	Cadaver	7	X- ray	12.7 ± 2.8	17.6 ±v2	
7	Dargel J, et al. [62]	2006	Cadaver	60	X-Ray / Image processing software			114.6 ± 44.93(L); 121.6 ± 49.12 (R)
8	Hemimg J F, et al. [53]	2007	Cadaver	12	Sharp point caliper	10.3 ± 1.5	18.5± 1.5	
9	Luites WH, et al. 1	2007	Cadaver	35	3D /3S space Fastrak electromagnetic tracking system			229 ± 53
10	Edwards A, et al. [66]	2007	Cadaver	55	High resolution scaled digital photograph/Comp uter graphics		18 ± 2	
11	Steckel H, et al. [47]	2007	Cadaver	6	Standard Micrometer	9 –14	17 – 25	
12	Siebold R, et al. [50]	2008	Cadaver	46	Digital photograph/ Digital image Analysis system	10 ± 2	14 ± 2	114 ± 2
13	Tallay A, et al. [67]	2008	Specimen (TKA)	36	Vernier caliper/ Digital image Analysis System	10.3 ± 1.9	19.5 ± 5	
14	Purnell ML, et al. 68	2008	Cadaver	8k	CT-3D model	7.4 ± 1.2	10.7 ± 1.3	
15	Stijak L, et al. [58]	2009	Cadaver	50	Sliding vernier calipers	13.5 ± 2.1	20 ± 2.6	
16	Frank RM, et al. [42]	2010	Pateints	100	MRI		14 ± 3 to 31 ± 4	

17	Kopf S, et al. 70	2011	Patients	137	Arthroscopy		17 ± 2	
18	Han Y, et al.	2012	Cadaver	8	Vernier callipers/MRI	9 ± 1 (C), 8 ± 1 (M)	14 ±2 (C), 14 ± 3 (M)	
19	Otsubo H, et al.[72]	2012	Cadaver	7	Photograph/ Image J software			119.1
20	Iriuchishi ma T, et al. 49	2012	Cadaver	12	Photograph/ Image J software			123.5 ± 12.5
21	Pujol N, et al. 71	2012	Cadaver	22	Manual measurement	11.1	13.4	117.9
22	Ahmed MAAS. [29]	2013	Patients / Cadaver	26/26	MRI/Digital Caliper	12.1 ± 2.1	18.3 ± 2.9	
23	Triantafyll idi E, et al. 41	2013	Cadaver	8	Photograph/ Image J program	10.85	11.71	127.1
24	Ichiba A, et al. [73]	2014	Patients	100	MRI		15.2 ± 1.9	
25	Yelicharla AKR, et al. 31	2014	Cadaver	72	Vernier Caliper	11.8 ± 1.8(M) 11.3 ± 1.6(F)	12.7 ± 1.5 12.2 ± 1.3	133.5 ± 8.3(M) 129 ± 8
26	Smilegski R, et al. [39]	2016	Cadaver	111	Vernier caliper	12.6	-	-
27	Widhalm HK, et al.74	2016	Patients	146	MRI/ arthroscope		16.6 ± 1.6(M)16.4 ± 1.4(A)	
28	Guenther D, et al. [75]	2016	Patients	100	MRI/ Customized ruler	10.2 ± 1.0 ;10.4 ± 0.9; 9.7 ± 1.4	1 ± 6.6 ± 1.3; 16.7 ± 1.3; 16.3 1.6	132.8 ±15.7; 136.7 ± 15.4; 123.8 ± 21.5
29	Iyaji PI, et al. 54	2016	Cadaver	31	Vernier calipers	11.5 ± 0.7	14.2 ± 2.4	
30	Tampere T, et al. [76]	2016	Cadaver	8	Contrast CT/3D scanning	-	-	159.2
31	Araki D, et al. [77]	2017	Cadaver	12	MRI/Laser	-	-	134.7 ± 22.9(M);135.2 ± 15.1(L)
32	Tashiro Y, et al. [78]	2017	Patients	50	MRI		-	182.7 ± 41.1
Range of total tibial surface area of ACL						114 mm to 182.7 mm^2		
Range of width of the ACL over tibial insertion						7.3mm to 13.5 mm		
Range of Length of the ACL over tibial insertion						13. 4 mm to 20 mm		

ACL: Anterior cruciate ligament, M: MRI, L: Laser, C: Vernier caliper

Table 6: Femoral insertion area of ACL

ACL: Anterior cruciate ligament. M: Male F: Female

No.	Authors	Year	Type of study	No of sample	Method of measurement	Femoral insertion of ACL		
						Width (mm)	Length (mm)	Surface area (mm^2)
1.	Muneta T, et al. 52	1997	Cadaver	16	Micrometer	-	-	93.3 ± 34.1
2.	Tan JL, et al. 51	1998	Cadaver	30	Vernier caliper	10.4 ±3.1	13.9 ± 4	
3.	Harner CD, et al. 60	1999	Cadaver	5	Electromagnetic system/ 3D system	-	-	113 ± 27
4.	Colombet P, et al. [55]	2006	Cadaver	7	Vernier Caliper	9.3 ± 7.1	13.9 ± 9.5	
5.	Dargel J, et al. 62	2006	Cadaver	60	X-Ray Image processing software	-	-	95.8 ± 37.42 (L) 101.9 ± 35.13(R)
6.	Luites WH, et al. [1]	2007	Cadaver	35	3D /3S space Fastrak Electromagnetic tracking system	-	-	184 ± 52
7.	Steckel H, et al. 47	2007	Cadaver	6	Standard micrometre	6 – 13	13 – 25	
8.	HemingJF, et al. 53	2007	Cadaver	12	Sharp point caliper	9.5 ± 2.5	18.4 ±0.6	
9.	Ferretti M, et al. 64	2007	Cadaver	16	Laser 3D digitized	9.9 ±0.8	17.2 ±1.2	96.8 ± 23.1
					camera and software			
10.	Edward A, et al. 65	2008	Cadaver	22	Photographs/ Computer graphics	7 ± 1	14 ± 2	
11.	Purnell LM, et al. [68]	2008	Cadaver	8	CT scan/3D	7.6 ± 1.4	12.9 ± 0.9	
12.	Seibold R, et al. 50	2008	Cadaver	46	Photograph/ Image analysis system	8 ± 2	15 ± 3	83 ± 19
13.	Stijak L, et al. 58	2009	Cadaver	50	Vernier calipers	6.8 ± 0.7	20 ± 2.6	
14.	Iwahashi T, et al. 69	2010	Cadaver	8	CT Scan/ Image analysis/3 D Bone surface Model	8 ± 0.5	17.4 ± 0.9	128 ± 0.5
15.	HanY, et al. 80	2012	Cadaver	8	Vernier caliper/3D MR	6 ±1(C),6 ± 1(3D)	14 ±2(C), 15 ± 2(3D)	
16.	Otsubo H, et al. 72	2012	Cadaver	7	Photograph/ Image J software			124.6
17.	Pujol N, et al. 71	2012	Cadaver	44	Manual measurement	9.1	13.1	96.8
18.	Sasaki N, et al. 56	2012	Cadaver	20	Digital Calipers	4.6 ±7	17.7 ± 2.7	
19.	Iriuchishima T, et al. 49	2012	Cadaver	12	Image J software	-	-	60.1 ± 16.9
20.	Ahmed	2013	Patients/ Cadaver	26/26	MRI/Digital caliper	9.3 ± 1.1	17.3 ± 1.7	
	MAAS. 29							
21.	Triantafyllidi E, et al. 41	2013	Cadaver	8	Photgraph/ Image J program	8.22	3.54	29.1
22.	Mochizuki T, et al. [81]	2013	Cadaver	6k	Image J software			142.2
23.	Yelicharla AKR, et al. [31]	2014	Cadaver	72	Vernier Caliper	8.3± 1.4(M) 8.2 ±1.1(F)	3.8 ±0.9(M) 3.2 ±0.69(F)	29.1±3.29 (M)30.2 ± 3.5(F)
24.	Kawaguchi , et al. [57]	2015	Cadavers	8	Scale	4.3 ± 0.9	17.9 ± 2	–
25.	Iyaji PI, et al. 54	2016	Cadavers	8	Vernier caliper	9.0 ± 1.1	14.4 ± 2.2	–
26.	Smilegski R, et al. [39]	2016	Cadaver	6	Vernier caliper	16	–	–
Range of total femoral insertion area of ACL						29.1mm2 to 196 mm^2		
of the ACL in femoral insertion site						4.3mm to 10.4 mm		
of the ACL in femoral insertion site						12.9 mm to 18.3 mm		

Table7: Number of bundles in anterior cruciate ligament

No.	Authors	Year	Type of study	No of sample	Method of measurement	No of Bundles
1.	Luites WH, et al. [1]	2007	Cadaver	35	3D /3S space Fastrak electromagnetic tracking system	2
2.	Steckel H, et al. [2]	2007	Cadaver	6	Blunt dissection/Motion of knee	2
3.	Kaya A, et al. [6]	2010	Patients	150	1.5 MRI	1 = 93; 2 = 57
4.	Otsubo H, et al. [72]	2012	Cadaver	7	Blunt dissection	3
5.	Adriaensen MEAPM, et al. [3]	2012	Patients	50	3TMRI	2
6.	Kato Y, et al. [8]	2012	Cadaver	10	Blunt dissection and arthroscopy	3
7.	Ng AW, et al. [4]	2013	Cadaver/Subjects	5©,24(M)	MRI/Direct method	2
8.	Tantisricharoenkul G, et al. [9]	2013	Cadaver	10	Penfiled/wireloop	3
9.	Hara K, et al. [5]	2015	Cadaver	20	String	2
Ranges of Number of bundle					2 to 3	

C: Cadaver, M: Male.

Table 8: Tibial Insertion of bundles

No	Author	Year	Type of study	No of sample	Method of measurement	AM			PL		
						Length (mm)	Width (mm)	SA (mm2)	Length (mm)	Width (mm)	SA (mm2)
1	Harner CD, et al. 60	1999	Cada ver	10	Electromag netic system/ 3D sytem	-	-	56 ± 21	-	-	53 ± 21
2	Takahashi M, et al. 63	2006	Cada ver	100	Photograph/ MacSCOPE software	-	-	67 ± 18.4	-	-	52.4 ± 17.6
3	Luites WH, et al. [1]	2007	Cada ver	35	3D /3S space Fastrak Electromag netic tracking system	-	-	136 ± 37	-	-	93 ± 33
4	Steckel H, et al. [2]	2007	Cada ver	6	Standard Micrometre	-	-	69.3	-	-	55.7
5	Seibold R, et al. 50	2008	Cada ver	46	Photograph/Image analysis system	12 ± 2	5 ± 1	67 ±31	10 ± 2	**4 ± 1**	52 ± 20
6	Kopf S, et al. [70]	2012	ACL reconstructed pts	137	Arthroscop ic bendable Ruler	9.1	9.2	-	7.4	**7**	-
7	Lee JK, et al. [79]	2015	Cada ver	15	Anatomic dissection	14.6 ± 3.3	6.7 ± 1.3	75.9 ± 22.4	14.9 ± 3.2	6.2 ±1.4	73.3 ± 22.9
					Radiograp hy	13.9 ± 3	7 ± 1.1	77.7 ± 19.3	14.3 ± 2	6.5 ±1.6	75.2 ±19.7
					3D CT	13 ± 1.3	6.5 ±1.1	71.8± 19.9	13.1 ± 2.3	6.1 ± 1	71.6 ± 18.8
8	Iyaji PI, et al. 54	2016	Cada ver	31	Vernier Caliper	8.9	9.8	-	9.3	8	-
Range of width of AM bundle						5 mm to 9.8 mm					
Range of length of AM bundle						8.9mm to 14.6 mm					
Range of surface area of AM bundle						$56mm^2$ to 136 mm^2					
Range of width of PL bundle						4 to 8 mm					
Range of Length of PL bundle						7.4mm to 14.9 mm					
Range of surface area of PL bundle						52 to 93 mm^2					

AM: Anteromedial bundle, PL: Posterolateral bundle.

Table 9: Femoral insertion of bundles

No.	Author	Year	Type of study	No of sample	Method of measurement	AM Length (mm)	AM Width (mm)	AM SA (mm^2)	PL Length (mm)	PL Width (mm)	PL SA (mm^2)
1	Harner CD, et al. 60	1999	Cadaver	10	3D system/ Electromagnetic system			47 ± 13			49 ±13
2	Takahashi M, et al. 63	2006	Cadaver	100	Photograph / MacSCOPE software	11.3 ± 1.6	7.5 ± 1.3	66.9 ± 2.3	11 ± 1.7	7.6 ± 1	66.4 ± 2.3
3	Mochizuki T, et al. [82]	2006	Cadaver	20	Measuring scale	9.2 ± 0.7	4.7 ± 0.6		6 ± 0.8	4.7 ± 0.6	
4	Luites WH, et al. [1]	2007	Cadaver	35	3D /3S space Fastrak electromagnetic tracking system			81 ± 27			103 ± 39
5	Steckel H, et al. [2]	2007	Cadaver	6	Standard micrometre	-	-	66	-	-	52.3
6	Ferretti M, et al. 64	2007	Cadaver	16	Laser 3D digitized camera and software	9.8 ± 1		120 ± 19.8	7.3 ± 0.5		76.8 ± 15.6
7	Edwards A, et al. [65]	2008	Cadaver	22	Photograph / computer graphics	7.6 ± 1.5	7 ± 1		6.2 ± 2.3	5.5 ± 3.1	
8	Seibold R, et al. 50	2008	Cadaver	46	Photograph /Image analysis system	7 ± 1	7 ±1	44 ± 13	7 ± 2	7 ± 1	40 ± 11
9	Kopf S, et al. 70	2011	ACL reconstructed pts	137	Arthroscopic bendable Ruler	9.2	8.9		7.1	6.9	
10	Lee JK, et al. 79	2015	Cadaver	15	Anatomic Dissection	12.2 ± 1.4	7 ± 1.3	70.3 ± 10.9	12.2 ± 2.5	6.9 ± 0.9	67.4 ± 17.9
					Radiography	11.3 ± 1	6.5 ± 1	63.4 ± 10.5	11 ± 1.6	6.4 ± 1	62.4 ± 14.2
					3D CT	10.6 ± 1.2	6.3 ± 1	60.2 ± 10.4	10.7 ± 1.8	6.3 ± 0.8	60.1 ± 14.7
11	Iyaji PI, et al. 54	2016	Cadaver	31	Vernier Caliper	8.3	7.7		7.8	6.9	
	Range of width of AM bundle					4.7 mm to 8.9 mm					
	Range of length of AM bundle					7 to 12.2 mm					
	Range of surface area of AM bundle					44 to 120 mm^2					
	Range of width of PL bundle					4.7 mm to 7.6 mm					
	Ranges of Length of PL bundle					6 mm to 11 mm					
	Surface area of PL bundle					40 to 103 mm^2					

AM: Anteromedial bundle, PL: Posterolateral bundle

Table 10: Summary of the reviewed morphometry of ACL and its bundles

No.	Parameter	Range of the parameter (observed from all studies)
1	length of ACL	30.35 to 36.88 mm
2	width of the ACL	5.9 to 16 mm
3	Number of bundles	1-3
4	Width of the anteromedial bundle	4.2 to 8.5 mm
5	Width of the posterolateral bundle	3.7 to 7.7 mm
6	Cross-sectional area of ACL	29.7 to 83.54 mm^2
7	Thickness of ACL	3.3 to 4.96 mm
8	Total tibial insertional surface area of ACL	114 mm to 182.7 mm^2
9	length of the tibial insertional area of ACL	13. 4 mm to 20 mm
10	Width of the tibial insertional area of ACL	7.3 mm to 13.5 mm
11	Total femoral insertional surface area of ACL	29.1 mm^2 to 196 mm^2
12	length of the tibial insertional area of ACL	12.9 mm to 18.3 mm
13	Width of the tibial insertional area of ACL	4.3 mm to 10.4 mm
14	Total tibial insertional surface area of anteromedial bundle of ACL	56 mm^2 to 136mm^2
15	length of the tibial insertional area of anteromedial bundle of ACL	8.9 mm to 14.6 mm
16	Width of the tibial insertional area of anteromedial bundle of ACL	5 mm to 9.8 mm
17	Total tibial insertional surface area of posterolateral bundle of ACL	52 mm^2 to 93 mm^2
18	length of the tibial insertional area of posterolateral bundle of ACL	7.4 mm to 14.9 mm
19	Width of the tibial insertional area of posterolateral bundle of ACL	4 mm to 8 mm
20	Total femoral insertional surface area of anteromedial bundle of ACL	44 mm^2 to 120 mm^2
21	length of the tibial insertional area of anteromedial bundle of ACL	7 mm to 12.2 mm
22	Width of the tibial insertional area of anteromedial bundle of ACL	4.7 mm to 8.9 mm
23	Total tibial insertional surface area of posterolateral bundle of ACL	40 mm^2 to 103mm^2
24	length of the tibial insertional area of posterolateral bundle of ACL	6 mm to 11 mm
25	Width of the tibial insertional area of posterolateral bundle of ACL	4.7 mm to 7. 6 mm