A CADAVERIC MORPHOMETRIC STUDY OF THE ATTACHMENTS OF THE ANTERIOR CRUCIATE LIGAMENT IN THE SOUTH INDIAN POPULATION

Dissertation Submitted to

THE TAMIL NADU DR. MGR MEDICAL UNIVERSITY,

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In partial fulfilment of the regulations for the

Award of the degree of

M.S. (ORTHOPAEDIC SURGERY)

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APRIL 2015

CERTIFICATE

This is to certify that **Dr. Bhide Pushkar Parag**, post-graduate student (2012 - 2015) in the Department of Orthopaedic Surgery, Kilpauk Medical College, had done dissertation on **"CADAVERIC MORPHOMETRIC STUDY OF THE ATTACHMENTS OF THE ANTERIOR CRUCIATE LIGAMENT IN SOUTH INDIAN POPULATION"**, under my guidance and supervision, in partial fulfilment of the regulation laid down by THE TAMILNADU DR.M.G.R. MEDICAL UNIVERSITY, CHENNAI – 32, for M.S. Orthopaedic surgery degree examination to be held in April 2015.

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Dr.SAMUEL GNANAM, M.S.(Ortho), D.Ortho,

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Dr. KARTHIKEYAN M. S. Ortho.

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Lastly, I thank the families of all the subjects who wholeheartedly donated their kin's bodies for the betterment of science without whom this study would not have been possible.

DECLARATION

I, **Dr. BHIDE PUSHKAR PARAG**, solemnly, declare that this dissertation titled **“CADAVERIC MORPHOMETRIC STUDY OF THE ATTACHMENTS OF THE ANTERIOR CRUCIATE LIGAMENT IN SOUTH INDIAN POPULATION”** is a Bona fide work done by me at Kilpauk Medical College, during the period from 2012 to 2015, under the guidance and supervision of my Unit Chief **Prof. K.RAJU,** M.S. (Ortho), D.Ortho. This dissertation is submitted to “THE TAMILNADU DR MGR MEDICAL UNIVERSITY”, towards partial fulfilment of regulations for the award of M.S.DEGREE BRANCH II in Orthopaedic Surgery.

Place: Chennai

Date :

DR. BHIDE PUSHKAR PARAG

Title: A CADAVERIC MORPHOMETRIC STUDY OF THE ATTACHMENTS OF THE ANTERIOR CRUCIATE LIGAMENT IN SOUTH INDIAN POPULATION

Keywords: Anterior cruciate ligament, cadaveric, ACL, knee, morphometric, South Indian population,

Introduction: Anterior cruciate ligament (ACL) reconstruction is one of the most common arthroscopic knee surgeries done in the World. As we acquire greater knowledge about the biomechanics of the ACL, it is increasingly apparent that the aim of a successful ACL reconstruction is restoration of the patient's anatomy.

The ACL has, for some time, been described as consisting of two main functional bundles- the Antero- medial (AM) and the postero- lateral (PL). These bundles have been shown to behave differently in the tensioning of their fibres in varying degrees of knee flexion and rotation. This has led to the development of the 'double bundle' ACL reconstruction technique, which is entirely dependent upon the **anatomical placement of tunnels** and differential tensioning for physiological load bearing patterns. The results of the more commonly done 'isometric' single bundle ACL reconstruction have also been shown to rely on the **placement of the femoral tunnel.**

As newer, more anatomical techniques evolve, a demand for quantitative anatomical description of the attachments of the ACL and its two bundles in

specific populations has arisen. Several papers in the Western population doing so have been published, but as all knees are not the same, regional data is warranted.

It is hypothesized that, because knees in a particular population are geometrically similar, measurements to locate the bundle attachments could be correlated with measurements that describe the size of the knee.

Materials and Methods: 22 preserved cadaveric knees with intact ACLs were dissected. The AM bundle was identified by anterior drawer in full external rotation and marked. The ACL was cut mid- substance and the knee subluxated. The lateral condyle was taken off and after cutting the remaining ACL, the femoral attachment of the ACL was measured with Vernier callipers and digitally photographed with a high resolution digital camera. The distances of the centre of the attachment from standard arthroscopic landmarks were also measured using callipers. The tibial attachment was similarly measured and photographed. The photographs were processed in the software AutoCAD (Autodesk Inc., San Rafael, Cal.) and the exact area of the attachments was calculated, along with the position of their centres along standard measurement grids. Maximum included diameter circles were plotted and the required graft diameter predicted.

To test the hypothesis, a Pearson coefficient was applied to the collected data in order to check the correlation of the measurements to the size of the knee.

Conclusion:

- We have inferred from this study that the **intra- articular landmarks** on the tibial plateau are a good initial point for the accurate location and placement of the tibial tunnel for both a single bundle and a double bundle ACL

  reconstruction.

- We have also presented useful data for the location and diameter of tunnel placement for the footprint for the femoral socket for ACL reconstruction.
- The use of this data, aided especially by an **Arthroscopic Ruler** or **adjustable guides** designed to reference from these landmarks, could be a remarkably useful method of consistently locating the tibial footprint. we encourage the arthroscopic surgeon to have the arthroscopic ruler as an important part of the ACL armamentarium.
- The data measuring the location of the footprints with relation to anatomic landmarks may be very useful in the future as baseline references for **Computer Navigated ACL Reconstruction** in South Indian patients.

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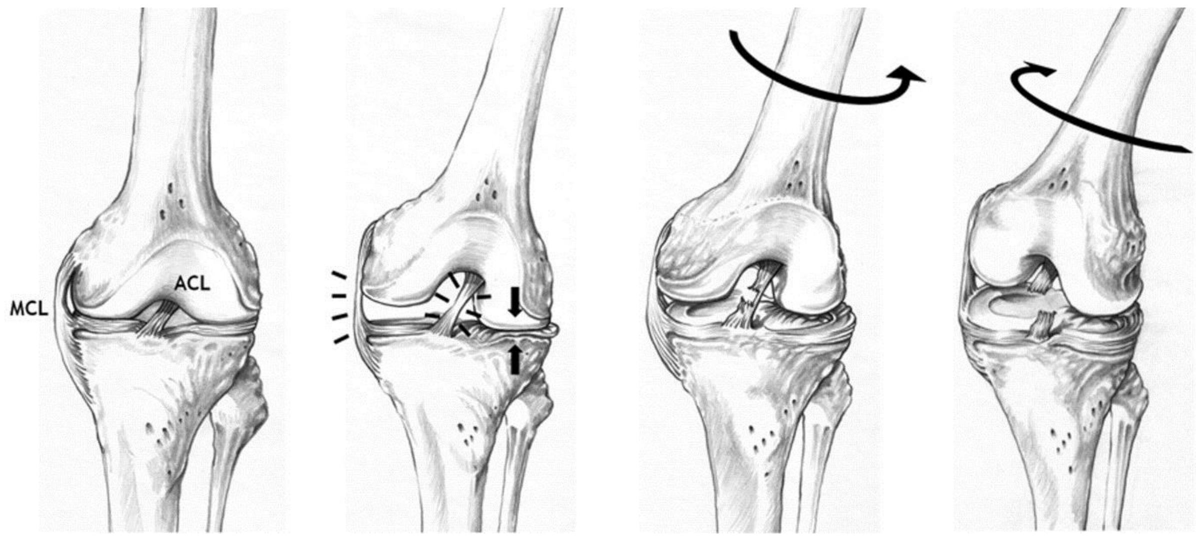
Introduction

The Anterior Cruciate Ligament (ACL) is an important ligament in the knee and plays a major role in the translational and rotational kinematics of knee movement. It is an intra- articular but extra- synovial ligament. It extends from the mid- anterior aspect of the tibial plateau to the medial aspect of the lateral femoral condyle in the inter-condylar notch.

The exact incidence of ACL injury is unknown, but it is one of the most commonly injured ligaments in the knee, superseded in incidence only by the MCL[1]. It is seen more in females after matching for activity level. Approximately 50% of patients with an ACL tear also have a concomitant injury. An ACL tear is usually a result of a low velocity, non—contact deceleration injury or a contact injury with a major rotational component. It is an important sports injury secondary to twisting, valgus or hyperextension of the knee(fig.).



In an ACL tear following a non- contact injury the patient gives a typical history of a 'popping' sound from the knee occurring on twisting, landing or cutting. A huge swelling of the knee follows immediately and the patient is unable to return to sport without intervention, but is able to bear weight.

In a tear following a contact injury, the patient is usually unable to bear weight as the ACL tear is associated with injury to other ligaments and/ or fractures.

On clinical examination, an immediate effusion in the absence of a bony injury is believed to have a 72% correlation with an ACL tear[2].

A Lachman test, which is the only test done in an acute knee injury is positive, showing more anterior translation of the tibia as compared to the normal side. Other tests like the Anterior Drawer, Pivot Shift and its surrogates (Valgus-rotation test, Losse's test etc.) may be performed after 4 weeks[3]. The Dutch Orthopaedic Association[4] recommends a positive Lachman test, Pivot Shift test and Anterior Drawer test for a clinical diagnosis of an ACL tear.

An Antero- posterior and lateral radiograph of an isolated ACL tear is usually normal. Sometimes, it may exhibit an avulsion fracture of the lateral tibial condyle called a Segond lesion, which has now been shown due to injury to the extra- articular Antero- Lateral Ligament[5]. A Magnetic Resonance Image (MRI) is always indicated in any case of knee instability. It has a sensitivity of 90-

98% for ACL tears[2]. The MRI shows ligament edema, non-visualization of the whole or part of the ACL and associated lesions of the menisci and/ or the articular cartilage. There may be some bone marrow edema.

Treatment:

Throughout the years, the treatment of an ACL tear has been shown to be total replacement of the ACL- a popular operation called ACL Reconstruction

A brief history of the treatment methods of ACL tears is presented here[6]:

1898- W. Battle- Sutured a torn ACL

1912- K. H. Giertz- Extra- articular reconstruction using fascia lata

1913- V. Nicoletti- Technique for use of autologous tendon as graft

1917- Hey Groves- first ACL reconstruction performed using fascia lata

1921- Bircher- First knee arthroscopy

1934- Galeazzi- First ACL reconstruction using hamstring graft

1935- Campbell- First ACL reconstruction employing patellar tendon graft

1963- Jones- First ACL reconstruction using bone- patellar tendon- bone graft

1981- Dandy- First arthroscopic ACL reconstruction

Post 2000- Increasing interest in the anatomical configuration of the ACL as pivot shift persisted even after 'isometric' ACL reconstruction- The rise of Anatomical Technique

2003- Marcacci- First anatomical double bundle ACL reconstruction

2004- Yasuda- First article on anatomical positioning of graft tunnels

As is apparent, the focus in ACL reconstruction shifted from ‘joining the femur to the tibia’ to a more anatomic approach at the turn of the century[7]. Numerous functional and biomechanical reports have since proved that the best result in translational and rotational stability can be obtained by an anatomical placement of tunnels[8-13], whether single bundle or double bundle. As these observations were reported, a need for better understanding of the anatomy of the attachments of the ACL was uncovered. Many papers in the Western countries accurately described the attachment anatomy[8, 9, 14-17]. These papers led to the development of new instrumentation which has aided the Western arthroscopic ACL surgeon in placement of more anatomic tunnels[18]. Since the size of knees and consequently, the size and location of the ACL attachments differs from region to region, the studies done in the west may not be accurately applicable to the knees in South Indian Population.

Aim of the Study

Primary Objectives:

1) To estimate the measure of the area/ dimensions of the tibial and femoral footprints of the anterior cruciate ligament (as a whole and as the antero-medial and postero- lateral bundles) in the South Indian population
2) To describe the anatomical locations of the tibial and femoral footprints (as a whole and as the antero- medial and postero- lateral bundles) of the anterior cruciate ligament in the South Indian population

Secondary Objective:

3) To analyse the clinical application of the above measurements for the improved placement of tibial and femoral tunnels and to estimate the requisite graft diameter required during arthroscopic ACL reconstruction surgery in South Indian population.

Review of Literature

Embryologically, the development of the ACL has been proposed to start as early as 8 weeks of fetal life[19], which corresponds to O'Rahilly stages 21 and 22[20]. The ACL has been hypothesized to originate as a ventral condensation of the fetal blastema which migrates posteriorly as the femoral inter- condylar notch develops[20]. It is noteworthy that the menisci have also been proposed to develop from the same blastema condensation as the tibial insertion of the ACL, thus justifying the theory that both these structures act in conjunction[21].

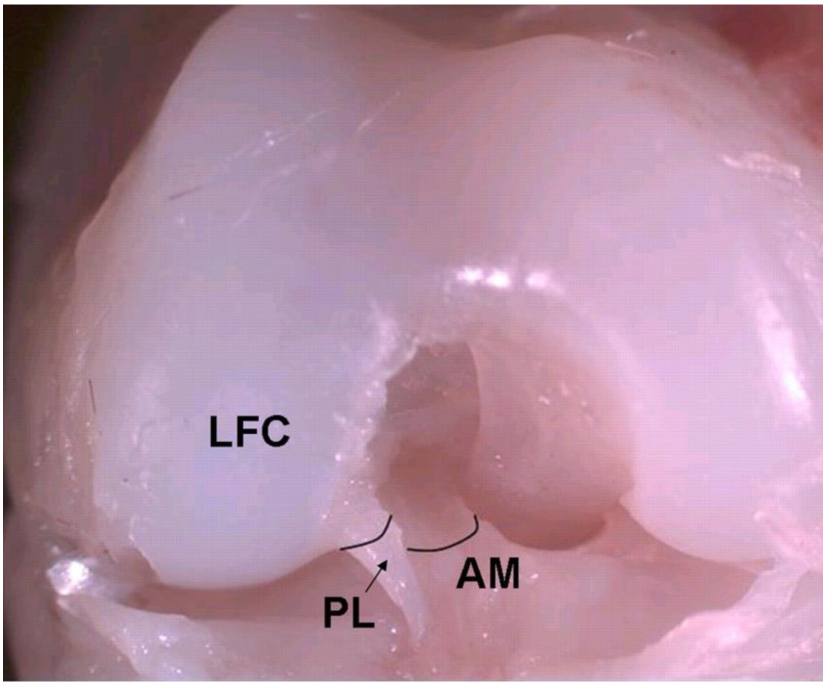
Another prominent theory regarding the development of the ACL, especially the femoral attachment, is that it develops from a confluence of collagenous ligament fibres and the periosteum of the femur[22]. After the initial formation, no major compositional or organizational changes occur in the ACL throughout the remaining part of fetal development[21].

The Fetal ACL

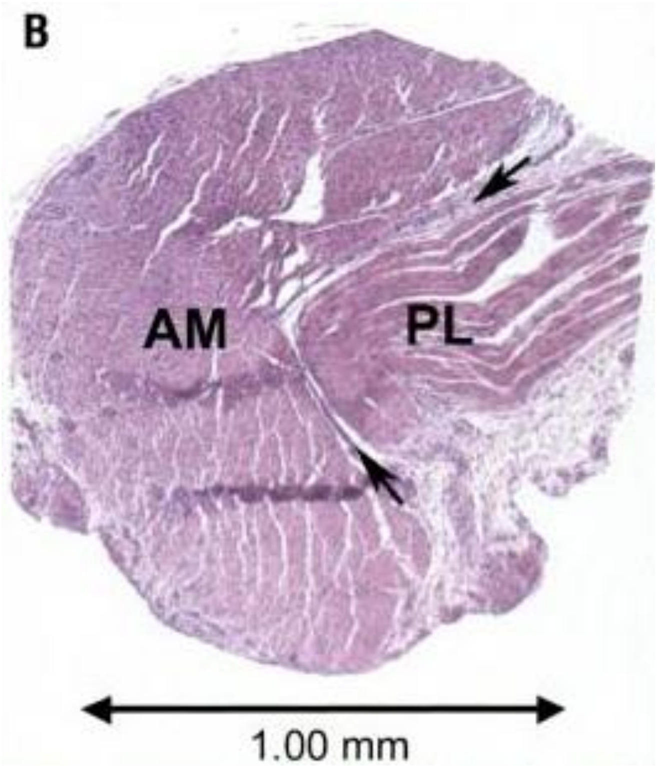
The study of the fetal ACL is an important guide to the development and functional divisions of the adult ACL. Fetal ACL has been shown to be covered with richly vascular synovial membrane. The middle genicular artery comes from the posterior capsule to enter the ACL and continues to its anterior extent and sends branches to the menisci. After removal of the lush synovium, 2 distinct antero- medial and postero- lateral bundles are observed[23].

The femoral attachment is located in the posterior part of the medial aspect of the lateral femoral condyle and the tibial attachment is located on the tibial plateau in between the 2 articular surfaces. Both the attachments are observed to be ovoid in shape. Unlike in the adult ACL, the bundles can be clearly demarcated in a fetal ACL, thus making its study invaluable to define the attachments of the individual bundles in the adult.

Several studies show that on the tibia, the Antero- medial bundle attaches posterior and slightly lateral to the attachment of the anterior root of the lateral meniscus[23]. The postero- lateral bundle attaches posterior and lateral to the antero- medial bundle and more- or- less in the centre of the tibial plateau. On the femur, the antero- medial bundle attaches posterior to the attachment of the postero- lateral bundle, thus leading to crossing of the 2 bundles in the midsubstance of the ACL. The femoral attachment demonstrates a faint, but clearly identifiable bony ridge which separates the 2 bundles.



Histologically, the fetal ACL is extremely cellular with around 5600 cells/ mm^3. The cells are fusiform, ovoid to round. It is richly vascular. The 2 bundles can be clearly defined in the transverse as well as the sagittal sections. They have a richly vascularized connective tissue septum separating them.

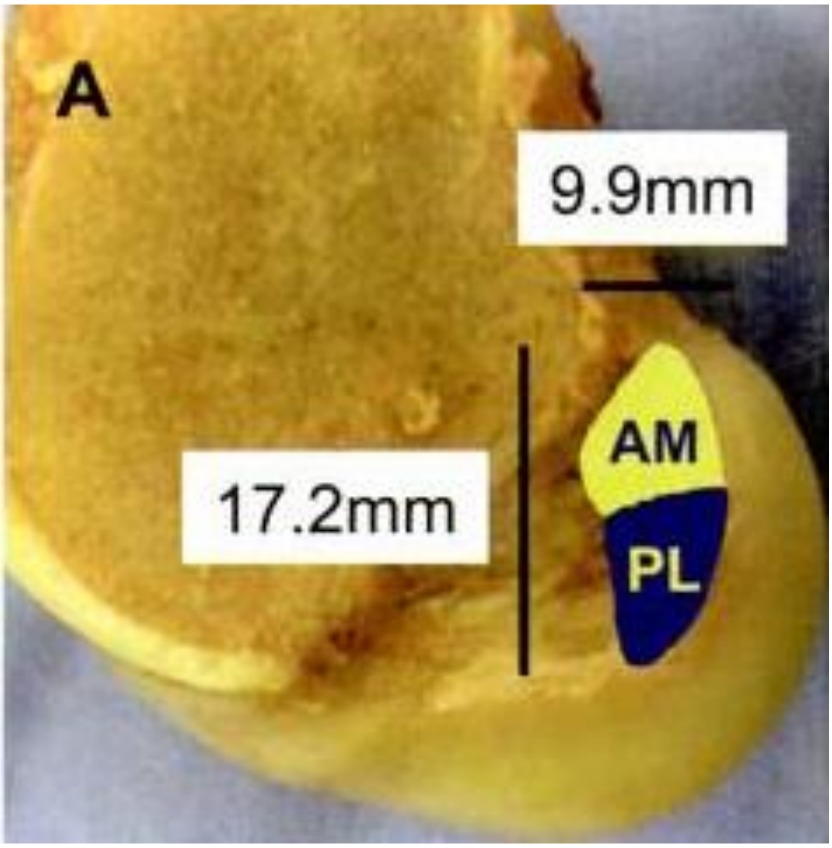


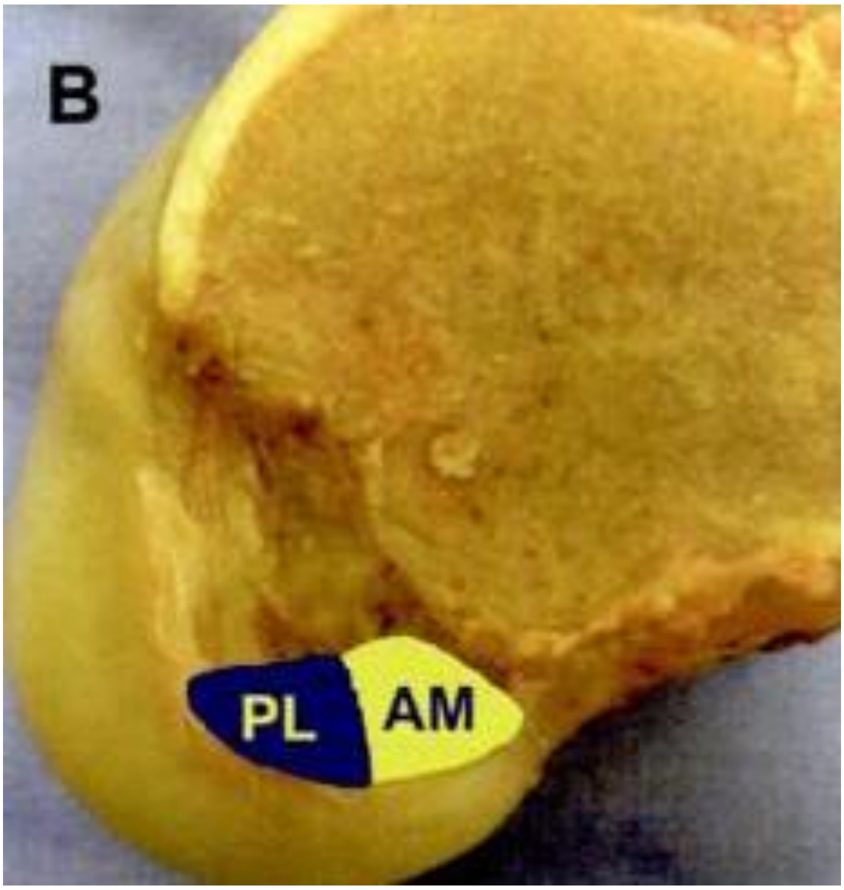
The histology of the tibial attachment demonstrates dense connective tissue. The femoral attachment, by contrast, shows the presence of less dense connective tissue at the transitional zone between ligament and cartilage [23].

The Adult ACL- Femoral Attachment

The femoral attachment of the adult ACL is large and ovoid and lies in the posterior portion of the medial aspect of the lateral femoral condyle.

Harner et al[24] and Odenstein and Gillquist[25] used laser digitization to map out the footprint. Their findings were that the femoral footprint is 18 mm long and 11 mm wide, with an area that is 3.5 times its mid- substance cross section.





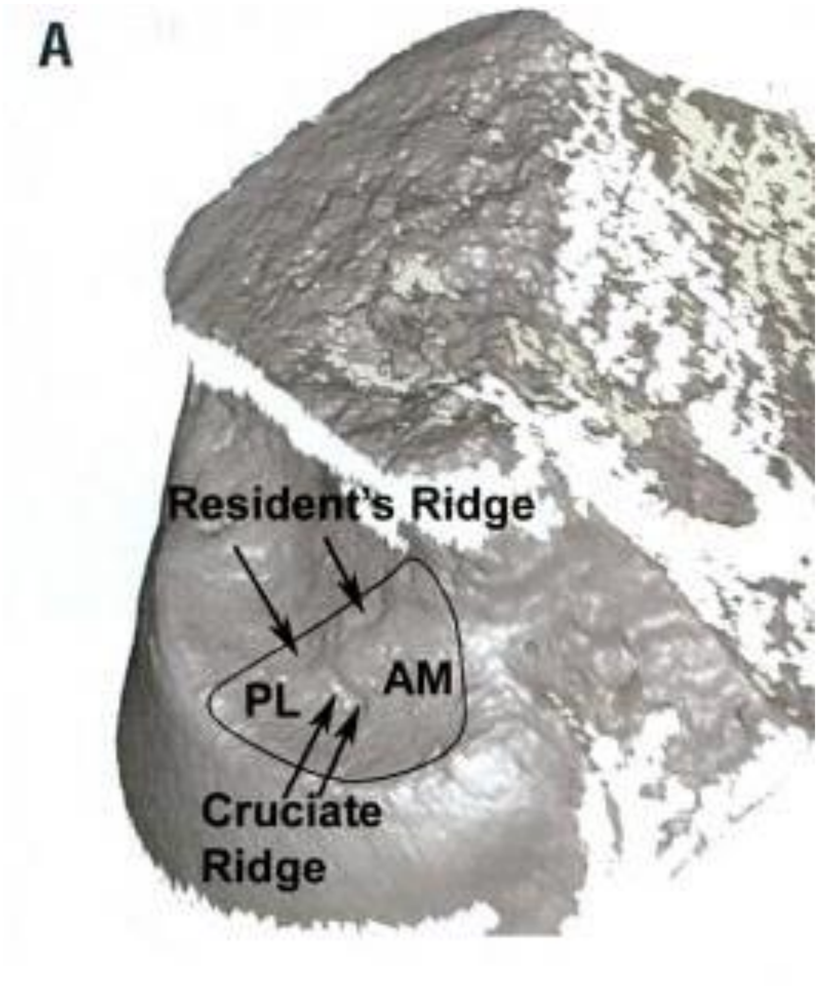
Histologically, it was found to extend from the intercondylar line superiorly to the articular cartilage inferiorly[26]. Bernard et al[27] performed a radiographic study of the femoral attachment of the ACL in which they found out that the centre of the footprint lies in the most postero- superior quadrant of the intercondylar fossa, at 24.8% of the distance between the roof of the intercondylar notch and the contour of the lateral femoral condyle and at 25.8% of the height of the lateral femoral condyle as defined by the distance from the inferior border of the condyle to the Blumensaat line on a true lateral radiograph of the knee.

The relationship between the 2 bundles of the ACL varies with the position of the knee. In an extended knee, the AM bundle attachment is oriented proximal and anterior to the PL bundle attachment. But in a flexed knee, as is seen during arthroscopy, the PL bundle is perceived as being ‘shallower’ and ‘lower’ than the AM bundle attachment on the lateral condyle[28]. They found the distance between the centres of the bundles to be 8-10 mm[29].

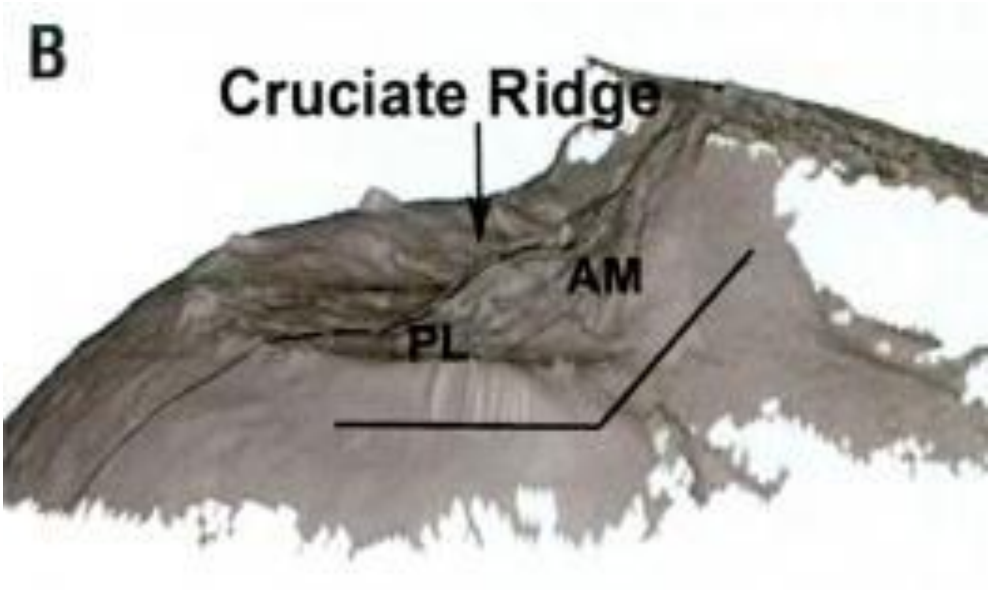
Previously, the O’clock position was used to describe the location of the femoral footprint. Using that system, the centre of the AM bundle was described to lie at 10:30 position in the frontal plane. The PL bundle was more difficult to define as its position changed with the change in position of the knee. In the extended position, its centre was described to lie approximately at the 9:30 position, about 8mm anterior to the articular cartilage[10, 26, 30].

Studies by Ferretti et al[31] have described the femoral origin in great detail using topographic analysis. They have found that the ACL is attached in a fossa on the posterior surface of the medial aspect of the lateral femoral condyle. They found a consistent bony prominence between the attachments of the AM and PL bundles, called the cruciate ridge[31]. This ridge was often more prominent in the anterior part of the footprint, as also correlated with fetal histological ACL studies.

The lateral intercondylar ridge is a bony ridge situated just anterior to the femoral attachment of the ACL. Histologically, no fibres of the ACL have been shown to be attached anterior to this ridge.



It is noteworthy that there is a change in topographical slope between the attachments of the AM and PL bundles. The plane of the AM bundle insertion is curved with a specific ratio.



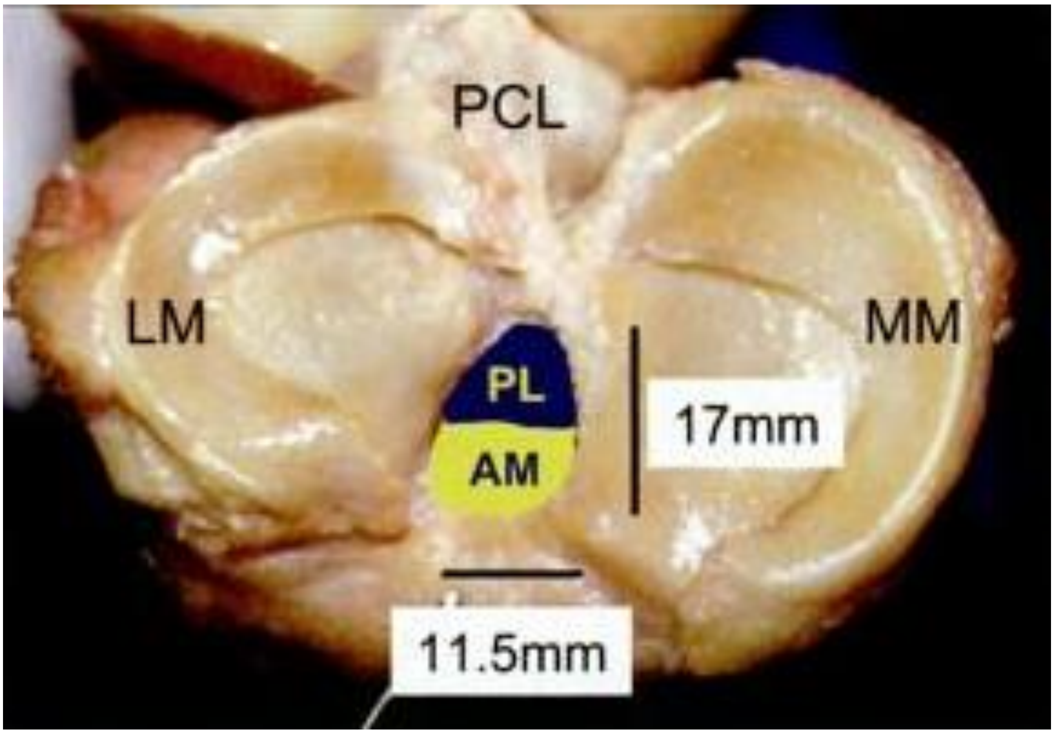
Some 3 dimensional studies have confirmed the presence of the cruciate ridge and the lateral intercondylar ridge by a laser 3D picture of the lateral femoral condyle. The change in the topography was also confirmed in the 3D studies.

Ferretti et al[31] derived the following measurements of the ACL femoral footprint based on their 3D laser study:

Quantitative Analysis of the Femoral Attachments of ACL		
	Mean	Range
Footprint Length (mm)	17.2 +/- 1.2	19 to 14.7
Footprint (mm)	9.9 +/- 0.8	11.5 to 8.4
AM Major Axis(mm)	9.8 +/- 1	11.7 to 8.1
PL Major Axis(mm)	7.3 +/- 0.5	8.3 to 6.6
Resident's ridge(mm)	14.9 +/- 2	17.5 to 12
Cruciate Ridge(mm)	5.7+/- 1.1	7 to 3.5
Footprint Area (mm^2)	196.8 +/- 23.1	230.4 to 158.1
AM Area (mm^2)	120 +/- 19.8	155.3 to 103.5
PL Area (mm^2)	76.8 +/- 15.6	118.7 to 54.5
Change of Slope (°)	27.7 +/- 8.9	40.9 to 11.8
AM Curvature Ratio (mm)	25.8 +/- 12	48.7 to 8.4

The Adult ACL- Tibial Attachment

The tibial attachment of the ACL is much wider and longer than the mid-substance or the femoral attachment. Harner et al[24] observed that the attachment of the ACL was about 120% larger than the femoral attachment and about 350% larger than the midsubstance ligament. It extends from almost the anterior border of the tibial plateau, where it fans out extensively, forming the foot region, to between the medial and lateral tibial spines, usually ending just anterior to the transverse interspinous ‘over the back’ ridge. It is triangular or oval in shape, with a diameter measuring between 10mm and 13mm in the frontal plane and 15mm to 19mm in the sagittal plane[24, 25, 28, 32, 33]



Staubli and Rauschning[12], in a landmark morphometric study using anatomic dissection, cryoplaning and contrast magnetic resonance arthrography, determined the dimensions of the tibial attachment of the ACL.

When measured from the anterior border of the tibial plateau, the ACL fibres were observed to start at 14.2mm +/- 4.2 mm, the centre of the ACL footprint was located at 21 +/- 2.6 mm and the posterior limit was at 29 +/- 4.1 mm.

Morgan et al[34] and Jackson and Gasser[35] defined the central point of the attachment of the ACL as being located approximately 7 mm anterior to the anteriormost extent of the PCL when seen with the knee in 90^{o} flexion.

On lateral radiographs of the knee, the ACL attachment was proposed to lie between 25% and 62% of the total antero- posterior length. It was centered between 43% and 46% of the medio- lateral distance in an antero- posterior radiograph[12, 16, 36].

The Antero- medial and Postero- lateral bundles of the ACL are designated as per their position in the tibial attachment[26, 32, 37-39]. The fibres of the AM bundle insert in the antero- medial portion of the tibial ACL attachment and may sometimes be confluent with the anterior horn of the lateral meniscus[17, 32, 33, 40].

The AM bundle footprint has been observed to occupy 56mm^2 +/- 21 mm^2 (52%) of the total tibial attachment. It is centered around 13 to 17 mm from the anterior tibial edge and it is somewhat in line with the anterior horn of the lateral meniscus[24, 25, 28]. On a lateral X-ray, it is located at around 30% of the antero- posterior diameter of the tibial plateau[30]. The fibres of the postero-lateral bundle insert in the postero- lateral region of the tibial attachment and may be confluent with the posterior horn of the lateral meniscus[26, 28]. It lies somewhat in the centre of the tibial plateau. It has been shown to have an area of53 +/- 21 mm^2 (48%) of the total area of the tibial attachment of the ACL[24]. Arthroscopically, the centre of the PL bundle footprint has been shown to lie around 7mm to 8mm anterior to the posterior cruciate ligament substance[26, 28, 30, 33]. It is located at 23 to 25 mm posterior to the anterior tibial edge. On a lateral projection, it has been proposed to lie at about 44% of the maximum antero- posterior tibial diameter[30]. On AP radiographs, centres of both bundles have been shown to lie around the centre of the tibial plateau, with the centre of the PL bundle more central, while the centre of the AM bundle marginally medial to it[10, 28, 30, 33, 41, 42].

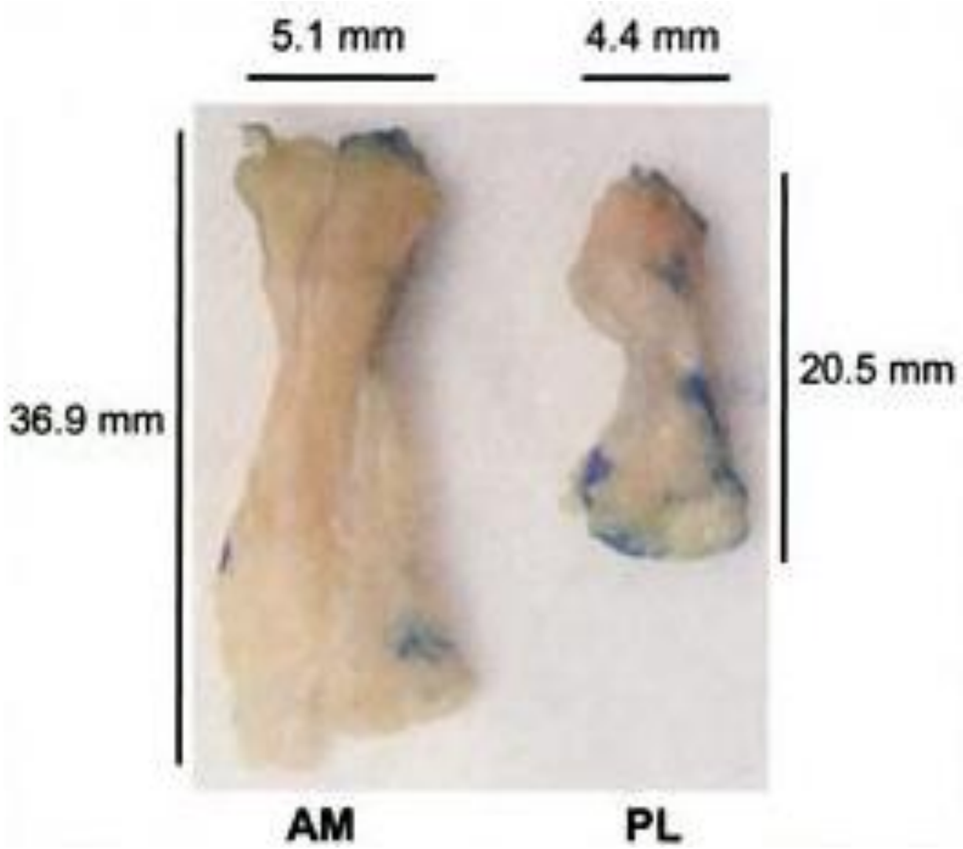
The Midsubstance of the ACL

Although the midsubstance of the ACL is not included in this study, it is essential to have a thorough understanding of the course of the ACL between the femoral and tibial attachments.

The ACL courses in an anterior, medial and distal direction as it passes through the intercondylar notch. The long axis of the ACL is directed at 26^o with relation to the vertical. It rotates over itself in a lateral spiral at almost 90^o as it approaches the tibial attachment[26, 28, 32, 33]. It is enveloped in synovial membrane throughout its course, making it intra- articular and extra-synovial[26, 32]. The diameter of the ACL is the narrowest at the midsubstance, ranging from about 7 to 12 mm[17, 25, 43]. It is oval in midsubstance, about 3.5 times smaller than the tibial attachment. It has an average area of 36 mm^2 in females and 44 mm^2 in males[24, 44].

Division of the ACL into 2 functional bundles- the antero- medial and the postero- lateral has been widely proven and accepted[10, 17, 26, 32, 33, 45-47]. These bundles are said to have varying degrees of tension among their fibres along varying degrees of flexion of the knee.

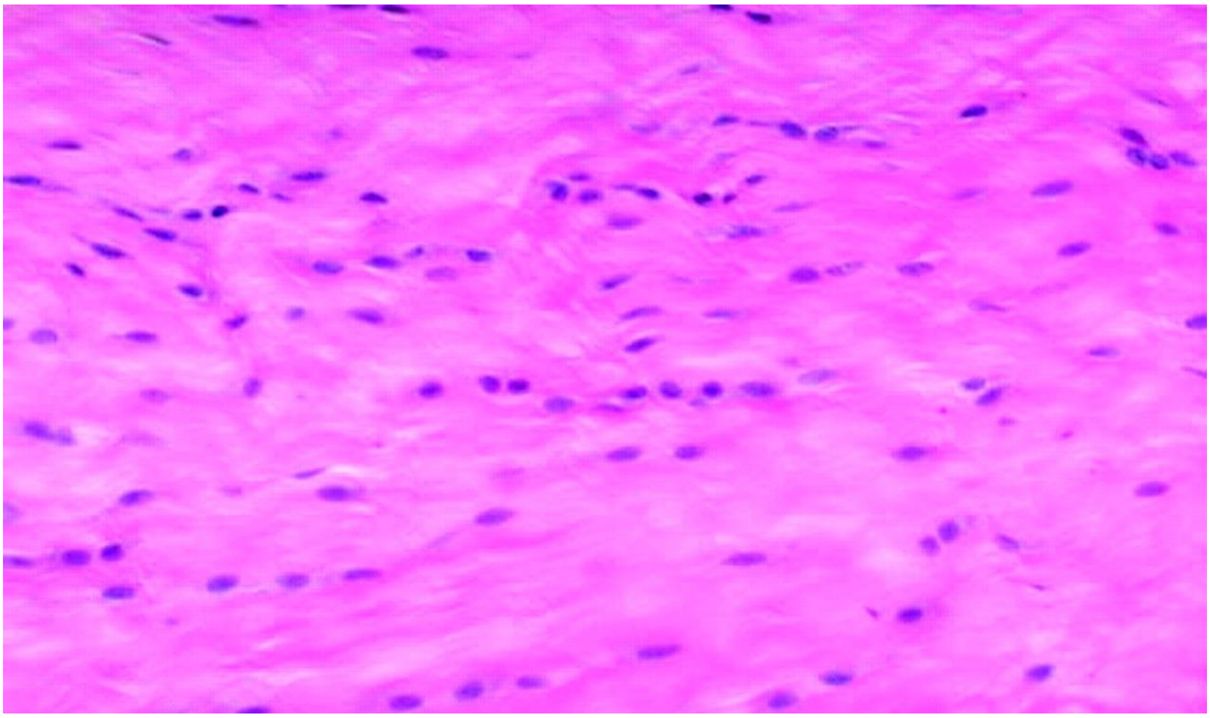
Cohen et al[48] performed an MRI study of the midsubstance of the ACL. They found that the AM bundle is 36.9 +/- 2.8 mm in length and 5.1 mm +/- 0.7 mm in width. The PL bundle averaged 20.5mm +/- 2.4 mm in length and 4.4 mm +/- 0.8 mm in width. The transverse diameter of the AM bundle was found to be 4.2 mm +/- 0.8 mm and that of the PL bundle was found to be 3.7 mm+/- 0.8 mm.



The AM bundle is shown to be more vertically oriented in the sagittal plane as compared to the more horizontal PL bundle.

Histology

Histologically, the ACL is composed of dense connective tissue. It consists of longitudinally oriented collagen fibrils ranging from a diameter of 20 to 70 microns and grouped together as bundles, surrounded by connective tissue, giving rise to multiple fascicles of the ligament[26, 37, 49, 50]. Further histological evaluation reveals that the ligament is surrounded by fibroblasts surrounded primarily by a matrix formed of Type I collagen and loose connective tissue containing type III collagen[37, 49, 51]. Small amounts of Type III and Type IV collagen are also observed near the femoral and tibial attachments[49, 51].



The transition region of ligament and bone at the attachments has been divided into 4 zones:

- **First zone**: Primarily collagenous ligament tissue
- **Second zone**: Fibrocartilagenous cells and collagen bundles
- **Third zone**: Mineralized fibrocartilagenous tissue
- **Fourth zone**: Mineralized fibrocartilage inserting into subchondral bone[52, 53]

Blood Supply

The blood supply to the ACL is predominantly through the middle genicular artery, a branch of the popliteal artery that enters the intercondylar notch by piercing the posterior capsule[54-56]. These vessels spread into a synovial plexus, which gives off small vessels which become inter ligamentous and travel along the direction of the collagen fibrils in the ACL[26, 37]. Secondary perfusion to the ACL is provided through the infra- patellar fat pad of Hoffa via branches from the inferior medial and lateral genicular arteries[55]. The femoral and tibial attachments themselves provide only minimal vascularity to the ligament proper.

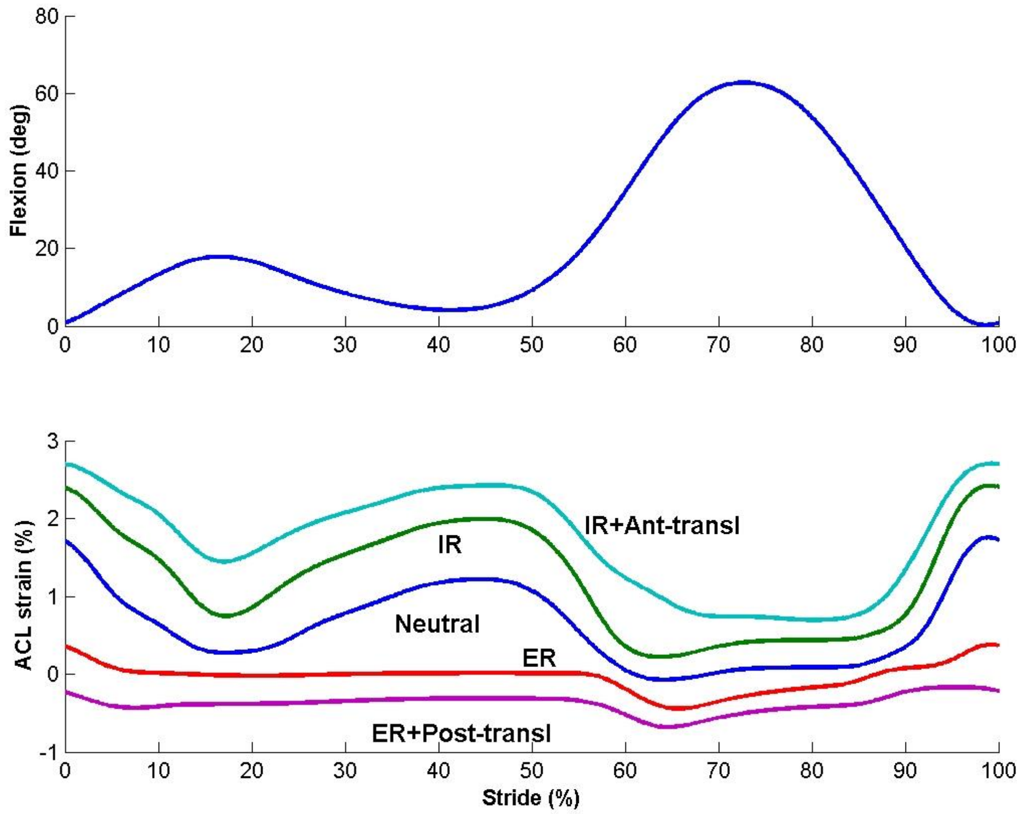
Nerve Supply

The ACL is supplied by branches from the posterior articular nerve, a branch of the tibial nerve which pierces the posterior capsule and gives rise to the popliteal plexus[32, 43]. The nerve fibres travel along with the blood vessels both in the synovial sheath and intra-substance[57, 58].

Nerve fibres similar to pain conducting fibres are found in the intra fascicular spaces of the ligament[43]. Mechanoreceptors are present on the surface of the ligament and have been found to be concentrated near the attachments, especially the femoral attachment[58, 59]. The role of these receptors has been recently described as being that of enhancing the stability of the knee partly by providing proprioception and partly through a sensory feedback loop controlling the muscle tone around the knee[60, 61].

Biomechanics

The ACL is the primary restraint against anterior translation of the tibia under the femur. The load bearing portion of the ACL has been shown to be a continuum of variously oriented collagen fibres. Although the fascicles appear to be homogenously aligned, the fibres are recruited differentially as external loads borne vary across the range of motion.

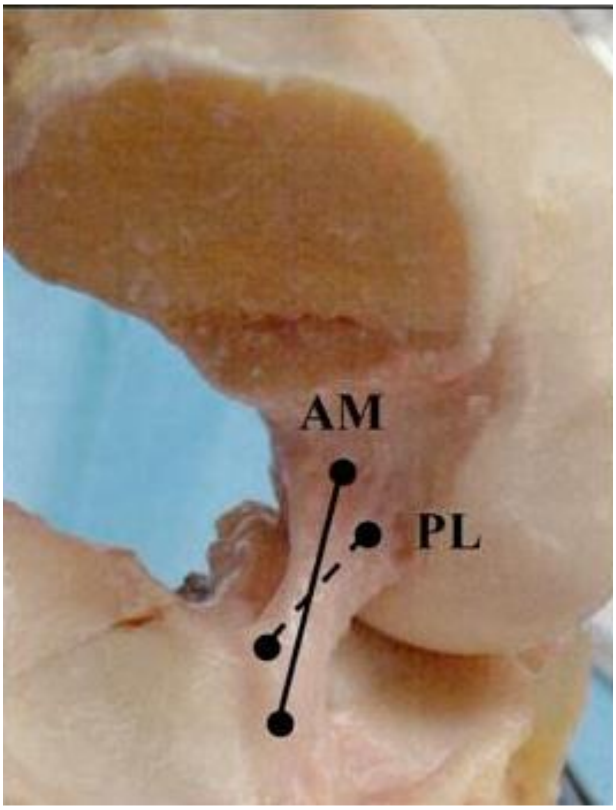


ACL Strain mapping during normal gait. Ant- transl: Anterior translation;

IR: Internal rotation; ER: External rotation; Post- transl: Posterior translation.

A number of bundles, ranging from 2 to 6 have been variously described. This distinction is purely functional, although some authors have noted the presence of synovium between the 2 bundles.

In full extension, the femoral attachment of the ACL is oriented vertically, thus making the PL bundle tight. As the knee begins to flex, the AM bundle is put on a stretch and responds by lengthening, while the PL bundle gradual shortens as it is relaxed[17, 29, 62-64]. The femoral attachment gradually becomes more and more horizontal as the knee is progressively flexed and at 120^{o} of flexion, the AM bundle reaches its maximum length and endures the maximum tension, while the PL bundle is under minimum strain[26, 28].



The gradual transition of ligament to bone consisting of 4 zones provides a gentle variation in stiffness of the tissue and prevents high concentration of stress at the attachment of the ACL[26, 32, 37, 38, 54].

Girgis et al[33] were the first to describe the functional anatomy of the ACL considering its functional bundles. They observed that while in full extension the whole ligament was taut, in 90o flexion, only the antero-medial portion of the ligament was under tension. They described this most 'isometric' portion of the ACL as the AM bundle.

Norwood and Cross[65] dissected 18 freshly amputated knees and described them functionally as consisting of 3 bundles- AM, intermediate and PL. Selective cutting of the bundles was performed to test their influence on the biomechanics of the knee. The AM and intermediate bundles were observed to be the primary restraints to the anterior translation of the tibia, whereas, the PL bundle when cut, led to more external rotation and recurvatum instability.

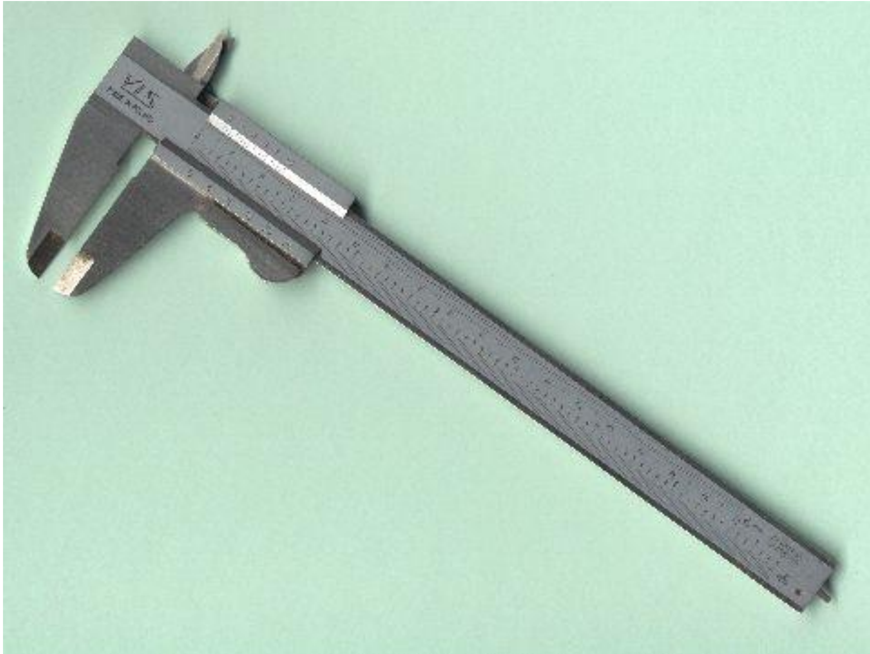
Materials and Methods

Sample Size: We used the formula $Z\alpha^2 \times SD^2 / Limit^2$ based on results of previous cadaveric studies as the basis to calculate our sample size for the descriptive study. As there are no cadaveric ACL studies till date published in India, we had to rely on various studies performed in developed countries. We accepted the maximum sample size of 22 knees for our study as representative of the South Indian population. This was in line with most of the studies performed[8, 11, 12]

22 unpaired cadaveric knees, ranging in age from 20 to 64 were employed for the purpose of this study. The knee was fixed on a customised vice. The quadriceps tendon was cut transversely about 5 cm above the patella. The remnant of the quadriceps tendon along with the patella was reflected inferiorly. The infra-patellar fat pad of Hoffa was excised. The capsule was dissected out till there was only posterior soft tissue contact between the femur and tibia. The synovium was dissected off the ACL till the fibres were seen clearly.

An anterior drawer test was performed after putting the leg segment in valgus and external rotation. The anterior fibres were observed to become taut differentially. These fibres were identified and marked with a silk suture in two places.

The midsubstance of the ACL was cut between the two marking stitches. The PCL was also cut and the knee subluxated anteriorly.



The following direct measurements were taken on the distal femur with a pair of Vernier callipers:

i) Epicondyar Width (mm)

ii) AP diameter of lateral condyle (mm)

iii) Femoral Inter- condylar Notch diameter (mm)

iv) Femoral Inter- condylar Notch height (mm)

The lateral condyle was then taken off with an electric sagittal saw through the midsagittal plane as described by Amis. The partition between the AM and PL bundles was further dissected down to the attachment. The ACL was further transected 1 to 2 mm from the tibial and femoral attachments. The division between the bundles was marked with paint using a fine brush.

On the tibia, the anterior fibres of the ACL were carefully tensioned with a pair of forceps and the junction of the fibres with the synovium was marked with paint. Posteriorly, the synovium was carefully dissected off and the posterior extent of the attachment was similarly marked, hence giving the complete tibial footprint including the 2 bundles.

Scaled photographs of the tibial plateau were taken with a digital still camera (Sony Corp., Minato, JP) and stored for further processing. The intersection points of the lengths and breadths of the whole footprint and the bundle footprints were marked as the centres of the respective footprints. Pertinent measurements were taken on the tibial plateau with a pair of Vernier Callipers by a single observer and recorded on a pre- decided proforma.

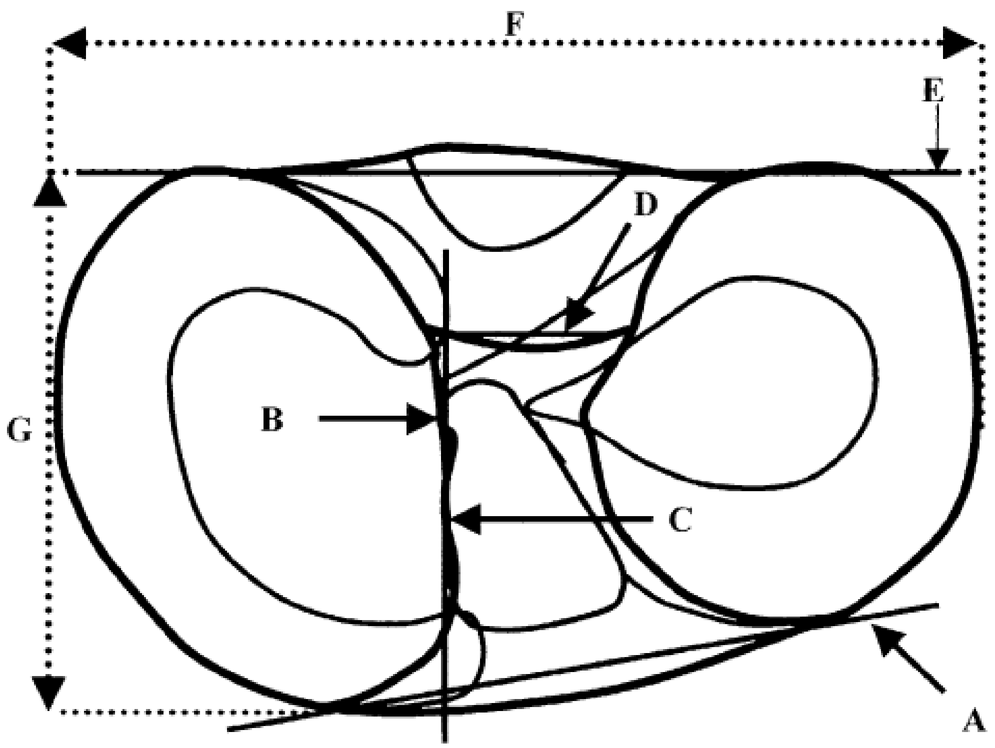


Fig. 3 Schematic diagram of the tibial plateau depicting the landmarks used in this study. *A* anterior tibial surface, *B* apex of medial tibial spine, *C* lateral border of medial tibial spine, *D* "over-the-back" ridge, *E* posterior tibial axis, *F* width, *G* depth

The following measurements were taken:

i) Tibial Plateau Width (mm): The medio- lateral width of the most proximal portion of the proximal tibia

ii) Tibial Plateau Depth (mm): The antero- posterior distance between the anterior border of the inter- meniscal ligament and the posterior tibial axis

iii) Distance of transverse interspinous ‘Over the back ridge’ from posterior tibial axis (mm)

iv) Tibial Footprint AP diameter (mm)

v) Tibial footprint ML width (mm)

vi) Distance of centres of bundles and whole footprint respectively from:

a) Posterior tibial axis (mm)

b) Anterior tibial border (mm)

c) Posterior border of the anterior horn of Lateral meniscus (mm)

d) Medial tibial spine apex(mm)

e) Transverse Inter- spinous ‘Over the back’ ridge (mm)

f) Anterior extent of PCL(mm)

The ACL fibres were now traced and differentiated from the synovium and articular cartilage of the separated lateral femoral condyle. The bundles and the whole footprint were marked as on the tibia and scaled photographs were taken and stored for processing. The centres of the footprints were marked as for the tibia. Measurements were similarly taken as on the tibia.

The following direct measurements were taken on the lateral femoral condyle:

i) AP width of femoral footprint (mm)

ii) Supero- inferior height of femoral footprint (mm)

iii) Measured distance of centres of footprints from:

   a) (Arthroscopically) Posterior Articular Cartilage margin

   b) (Arthroscopically) Inferior Articular Cartilage Margin

   c) Centre of the intercondylar ridge

The photographs were processed in AutoCAD software (Autodesk Inc., San Rafael, USA.). They were scaled to size and the area of the footprint marked by zooming and marking the footprint using a polygonal line.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Area = 181.6276, Length = 63.2698
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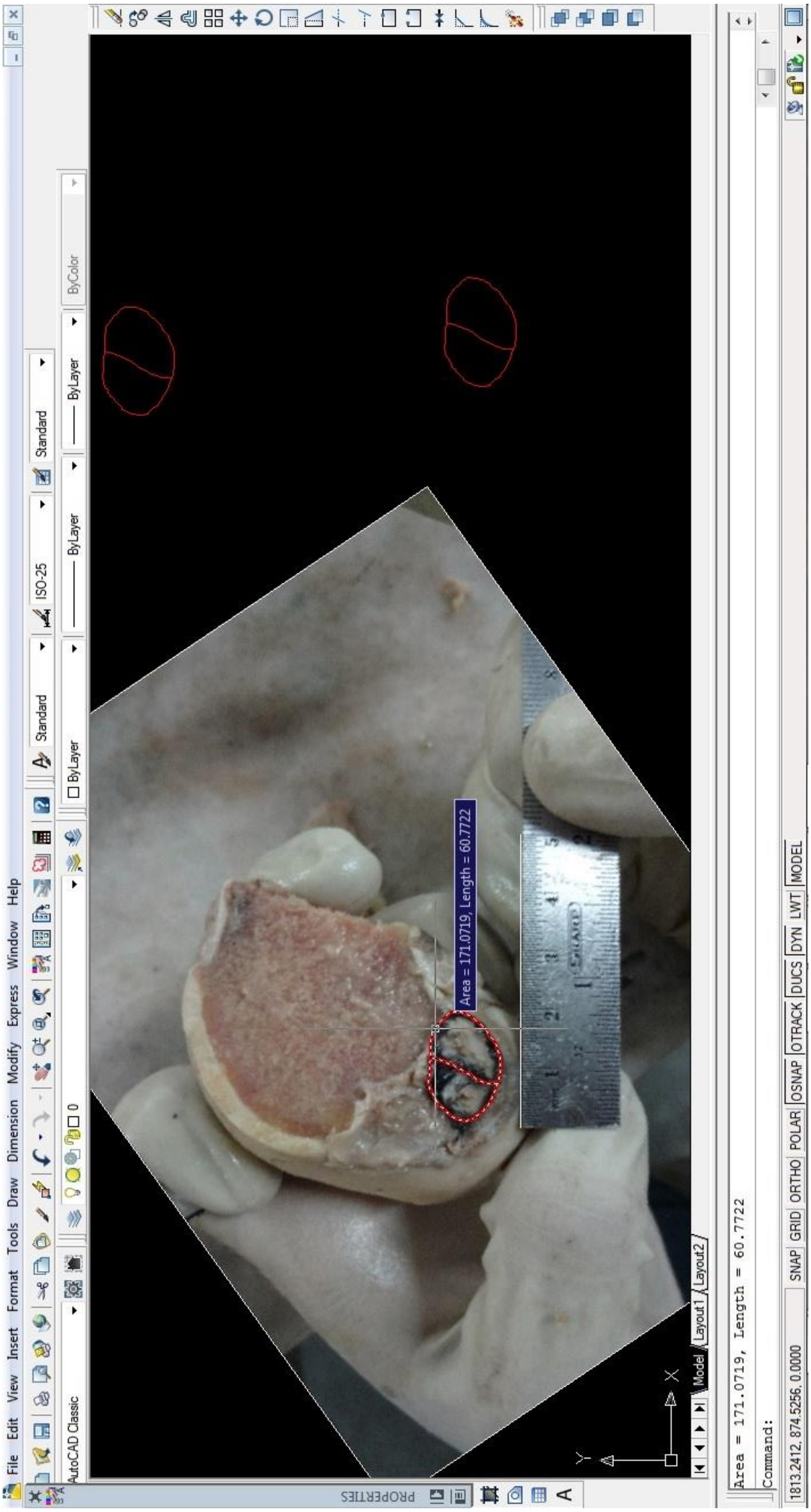
The following parameters were recorded in the tibial footprint from the software:

i) Tibial footprint pattern (mm):

ii) Area of footprint (bundles and as a whole) (mm^2):

The analysis of the photgraphs of the femoral footprint was more complex. The images were similarly scaled down and the basic area of the footprint computed as for the tibia.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PROPERTIES

The following variables were measured from the images using the software:

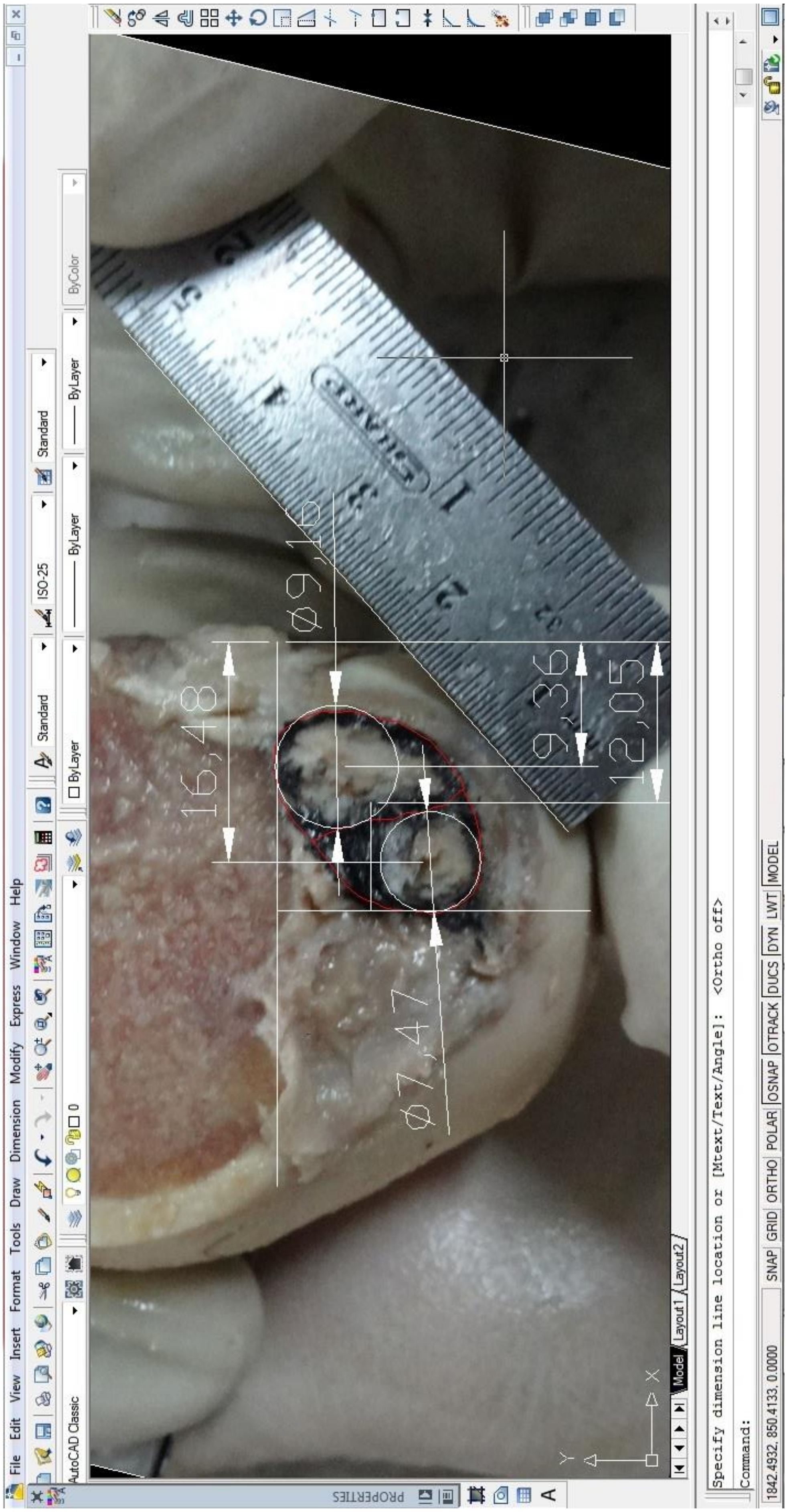
i) Posterior Lateral Condyle diameter reference (% Shallowness): A line was drawn along the roof of the intercondylar notch extending from the most anterior point to the most posterior point. Perpendiculars to this line from the centres of the footprint as a whole and the individual bundles were plotted and distance measured from the most posterior point and it was represented as a percentage of the line.

ii) Posterior Lateral Condyle diameter reference (% height): A line was drawn perpendicular to the roof of the intercondylar notch extending from the most distal point to the roof. Perpendiculars to this line from the centres of the footprint as a whole and the individual bundles were plotted and distance measured from the most distal point and it was represented as a percentage of the line.

iii) Position on (Amis) Measurement grid: A grid as described by Zavras and Amis[66] was plotted on the lateral femoral condyle and the centres of the footprints were plotted on the grid.

iv) Diameters of best- fit circles on AM and PL bundles: Two circles were plotted on the footprints of the AM and PL bundles respectively, touching the outlines of the footprints as much as possible. The diameters of these circles were measured. This was performed as a surrogate for the tunnels for the AM and PL bundles used in a double bundle ACL reconstruction.

v) Area of femoral footprint (mm^2): The whole footprint as well as the bundles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The data so collected was organized in MS Excel software (Microsoft Inc., Redmond, USA) and statistical analysis was applied to it. Mean and standard deviation were computed along with median and inter- quartile range. Hence descriptive data was obtained about the location and area of the femoral and tibial footprints.

For the secondary objective, in order to test the hypothesis that measurements to locate the bundle attachments could be correlated to the measurements for the size of the knee, correlation was examined using the Carl- Pearson correlation coefficient.

The independent variables (describing the size of the knee) that were considered were:

A) Tibia:

i) Tibial Plateau Width

ii) Tibial Plateau Depth

iii) Distance of transverse interspinous 'Over the back ridge' from posterior tibial axis

B) Femur

i) Epicondylar width

ii) Lateral condyle AP diameter

iii) Intercondylar notch width

iv) Intercondylar notch height

The dependent variables (describing the size and location of the footprint) considered were:

A) Tibia:

   i) Tibial Footprint AP diameter

   ii) Tibial footprint ML width

   iii) Area of footprint (bundles and as a whole)

   iv) Distance of centres of bundles and whole footprint respectively from:

      a) Posterior tibial axis (mm)

      b) Anterior tibial border (mm)

      c) Posterior border of the anterior horn of lateral meniscus

      d) Medial tibial spine apex

      e) Transverse Inter- spinous ‘Over the back’ ridge

      f) Anterior extent of PCL

The correlation of each of the dependent variables with each of the independent variables was checked along with P- value for significance. The correlation was taken to be statistically significant if the P value was less than 0.05. Based on the values, the hypothesis was tested.

Results

Primary Descriptive Analysis: Tibia

Parameter	Mean (Standard Deviation)	Median (Inter Quartile Range)
Tibial Plateau Width	75.6mm (4.3mm)	76.8mm (71.7mm-77.8mm)
Tibial Plateau Depth	46.7mm (3.8mm)	46.8mm (43.3mm-49.5mm)
Transverse Interspinous ridge- Posterior Tibial Axis	15.8mm (3mm)	15.7mm (13.2mm-18.3mm)
AP Diameter of footprint	19.6mm (1.5mm)	19.5mm (18.2mm-20.7mm)
ML Width of footprint	11mm (1.7mm)	11.2mm (9.8mm- 12mm)
Area- Whole footprint	$172.5mm^2$ ($27.5mm^2$)	$173.5mm^2$ ($152.6mm^2$-$191.6mm^2$)
Area- AM bundle	$95.8mm^2$ ($15.7mm^2$)	$95.2mm^2$ ($87.4mm^2$-$103.8mm^2$)
Area- PL bundle	$75.5mm^2$ ($17mm^2$)	$72.2mm^2$ ($64.7mm^2$-$83.2mm^2$)
Posterior Tibial Axis to Centre of footprint	26.6mm (3.7mm)	26mm (24mm- 30.5mm)
Posterior Tibial Axis to Centre of AM bundle	30.7mm (4.1mm)	30.1mm (28.6mm-33.8mm)
Posterior Tibial Axis to Centre of PL bundle	21.6mm (4mm)	20.9mm (18.6mm-25.7mm)
Anterior Tibial Border to Centre of footprint	22mm (3.3mm)	22.5mm (18.9mm-24.6mm)

Primary Descriptive Analysis: Tibia

Parameter	Mean (Standard Deviation)	Median (Inter Quartile Range)
Anterior Tibial Border to Centre of AM bundle	18.1mm (3.8mm)	18.4mm (15.4mm to 20.6mm)
Anterior Tibial Border to Centre of PL bundle	26.5mm (3.2mm)	27mm (23.3mm- 29.2mm)
Distance Medial from the Lateral Meniscus- Whole footprint	11.9mm (2.5mm)	11.8mm (11.3mm- 12.7mm)
Distance Medial from the Lateral Meniscus- AM bundle	12.1mm (2.5mm)	11.6mm (10.7mm- 12.5mm)
Distance Medial from the Lateral Meniscus- PL bundle	13.3mm (3.4mm)	13.9mm (11.3mm- 16.1mm)
Distance Lateral from the Medial Tibial Spine- Whole footprint	8mm (2.5mm)	7.2mm (6.2mm- 10mm)
Distance Lateral from the Medial Tibial Spine- AM bundle	9.3mm (2.7mm)	9.2mm (7.3mm- 10.9mm)
Distance Lateral from the Medial Tibial Spine- PL bundle	8.6mm (2mm)	8.6mm (6.8mm- 9.9mm)
Distance Anterior from Transverse Interspinous Ridge- Whole footprint	12.7mm (2.9mm)	12.1mm (11.3mm- 13.9mm)

Primary Descriptive Analysis: Tibia

Parameter	Mean (Standard Deviation)	Median (Inter Quartile Range)
Distance Anterior from Transverse Interspinous Ridge- AM bundle	16.9mm (3.1mm)	16.5mm (15mm- 17.8mm)
Distance Anterior from Transverse Interspinous Ridge- PL bundle	8mm (2.8mm)	7.4mm (6.3mm- 9.2mm)
Distance Anterior from the PCL- Whole footprint	16mm (2.7mm)	16.4mm (13.9mm- 17.7mm)
Distance Anterior from the PCL- AM bundle	19.5mm (3.5mm)	20mm (16.9mm- 21.2mm)
Distance Anterior from the PCL- PL bundle	11.4mm (2.7mm)	11.2mm (9.3mm- 14.2mm)

- **The Tibial Plateau Width:** The tibial plateau width was considered as an independent variable, representing the size of the knee on the tibial side. It ranged from 68 mm to 86.4 mm. The 22 tibiae considered had plateaux with a mean width of 75.6 mm with a standard deviation of 4.3 mm. The median was 76.8 mm with inter- quartile ranging from 71.7 mm to 77.8 mm.
- **The Tibial Plateau Depth:** The tibial plateau depth was also taken as an independent variable for the size of the tibia. It was seen to range from 40 mm to 54 mm with a mean of 46.7 mm and a standard deviation of 3.8 mm. The median was 46.8 mm with 25%- 75% readings lying between 43.3 mm and 49.5 mm (IQR).

- **Distance of Transverse Interspinous Over- the- back Ridge from the Posterior Tibial Axis:** This was taken as the third independent variable. It ranged from 10.7 mm to 21.7 mm. The mean ws found to be 15.8 mm with 3 mm of Standard Deviation. The median was 15.7 mm with the inter- quartile range from 13.2 mm to 18.3 mm.
- **The Tibial Footprint Antero- posterior diameter:** The tibial footprint sagittal diameter ranged from 17.5 mm to 22.8 mm. Its mean was 19.6 mm with a standard deviation of 1.5 mm. The median was 19.5 mm with IQR ranging from 18.2 mm to 20.7 mm.
- **The Tibial Footprint Medio- lateral width:** The medio lateral width of the tibial footprints ranged widely from 7.5 mm to 14.4 mm. The mean was 11 mm with a standard deviation of 1.7 mm. The median was 11.2 mm with an IQR of 9.8 mm to 12.1 mm.
- **The Area of the Tibial Footprint:** The AM bundle has been described to have almost equal cross sectional area in the ACL midsubstance as the PL bundle. It was found to greatly expand near the tibial end and attach over a larger area than the PL bundle.

  -The area of the whole footprint ranged from 117.3 mm^2 to 234.5 mm^2. The mean area was 172.5 mm^2 with a standard deviation of 27.7 mm^2.

The median area was 173.4 mm^2 with the IQR ranging from 152.6 mm^2 to 191.6 mm^2.

- The area of the AM bundle was found to range from 59.1 mm^2 to 126.9 mm^2. The mean was 95.8 mm^2 **(55.5% of the mean area of the whole footprint)** with a standard deviation of 15.7 mm^2. The median was 95.2 mm^2 with an IQR from 87.4 mm^2 to 103.8 mm^2.

- The area of the PL bundle was found to range from 44.9 mm^2 to 127.1 mm^2 with a mean of 75.8 mm^2 (**43.9% of the mean area of the whole footprint**) and an SD of 17 mm^2. The median was 72.2 mm^2 with an IQR from 64.7 mm^2 to 83.2 mm^2.

❖ **The Distance of the Centre of the Footprint from the Posterior Tibial Axis:**

- Whole footprint: The distance of the centre of the whole footprint from the posterior tibial axis ranged from 16 mm to 31.9 mm. The mean distance was 26.6 mm **(53.9% of the tibial plateau depth)** with a standard deviation of 3.7 mm. The median was 26 mm with an IQR from 24 mm to 30.5 mm.
- AM bundle: The distance of the AM bundle from the posterior tibial axis ranged from 20.3 mm to 37.9 mm with a mean distance of 30.7 mm and standard deviation of 4.1 mm. The median was 30.1 mm with an IQR of 28.6 mm to 33.8 mm

- PL bundle: The PL bundle was situated at a range of 13.5 mm to 26.9 mm anterior to the posterior tibial axis. The mean distance was 21.6 mm with an SD of 4 mm. The median distance was 20.9 mm with and IQR from 18.6 mm to 25.7 mm.

❖ **Distance of the Centre of the Footprint from the Anterior Tibial Border:**

  - The distance of the centre of the whole footprint from the anterior tibial border ranged from 15.5 mm to 26.9 mm. Mean distance was 22 mm **(47% of the tibial plateau depth)** with a standard deviation of 3.3 mm. Median distance was 22.5 mm with an IQR of 18.9 mm to 24.6 mm.
  - The AM bundle centre was situated at a range of 11.9 mm to 27.9 mm posterior to the anterior tibial border. Mean distance was 18.1 mm with a standard deviation of 3.8 mm. Median was 18.3 mm with an inter-quartile range of 15.4 mm to 20.6 mm.
  - The distance of the PL bundle from the anterior tibial axis ranged from 20.9 mm to 32.3 mm with a mean of 26.5 mm and a standard deviation of 3.2 mm. Median distance was 27 mm with an IQR from 23.2 mm to 29.2 mm.

- **The Distance of the Centre of the Footprint from the Posterior border of the Lateral Meniscus:**
  - Whole footprint: The distance of the centre of the whole footprint from the posterior border of the lateral meniscus ranged from 6.2 mm to 17.5 mm. The mean distance was 11.8 mm with a standard deviation of 2.5 mm. The median was 11.8 mm with an IQR from 11.3 mm to 12.7 mm.
  - AM bundle: The distance of the AM bundle from the posterior border of the lateral meniscus ranged from 8.9 mm to 18.9 mm with a mean distance of 12.1 mm and standard deviation of 2.5 mm. The median was 11.6 mm with an IQR of 10.6 mm to 12.5 mm
  - PL bundle: The PL bundle was situated at a range of 6.9 mm to 18.9 mm postero- medial to the posterior border of the lateral meniscus. The mean distance was 13.3 mm with an SD of 3.4 mm. The median distance was 13.9 mm with and IQR from 11.3 mm to 16.1 mm.
- **Distance of the Centre of the Footprint from the Apex of the Medial Tibial Spine:**
  - The distance of the centre of the whole footprint from the medial tibial spine ranged from 4.6 mm to 13.3 mm. Mean distance was 8 mm with a standard deviation of 2.5 mm. Median distance was 7.2 mm with an IQR of 6.1 mm to 10 mm.

- The AM bundle centre was situated at a range of 3.9 mm to 14.7 mm lateral to the medial tibial spine. Mean distance was 9.3 mm with a standard deviation of 2.7 mm. Median was 9.1 mm with an inter- quartile range of 7.2 mm to 10.9 mm.
- The distance of the PL bundle from the medial tibial spine ranged from 5.5 mm to 12.6 mm with a mean of 8.6 mm and a standard deviation of 2 mm. Median distance was 8.6 mm with an IQR from 6.8 mm to 9.9 mm.

❖ **The Distance of the Centre of the Footprint from the Inter- Spinous 'Over-the- back' Ridge:**

- Whole footprint: The distance of the centre of the whole footprint from the inter- spinous ridge ranged from 9 mm to 22.6 mm. The mean distance was 12.7 mm with a standard deviation of 2.9 mm. The median was 12.1 mm with an IQR from 11.3 mm to 13.9 mm.
- AM bundle: The distance of the AM bundle from the inter- spinous ridge ranged from 13 mm to 27.5 mm with a mean distance of 16.8 mm and standard deviation of 3.1 mm. The median was 16.4 mm with an IQR of 15 mm to 17.8 mm
- PL bundle: The PL bundle was situated at a range of 5 mm to 17 mm anterior to the transverse inter- spinous ridge. The mean distance was 8

mm with an SD of 2.7 mm. The median distance was 7.4 mm with and IQR from 6.3 mm to 9.2 mm.

- **Distance of the Centre of the Footprint from the Anterior Extent of the PCL Attachment:**
  - The distance of the centre of the whole footprint from the anterior extent of the PCL attachment ranged from 10.5 mm to 22.6 mm. Mean distance was 16 mm with a standard deviation of 2.7 mm. Median distance was 16.4 mm with an IQR of 13.9 mm to 17.8 mm.
  - The AM bundle centre was situated at a range of 10.9 mm to 27.5 mm anterior to the anterior extent of the PCL attachment. Mean distance was 19.5 mm with a standard deviation of 3.5 mm. Median was 20.1 mm with an inter- quartile range of 16.9 mm to 21.2 mm.
  - The distance of the PL bundle from the anterior extent of the PCL attachment ranged from 7.3 mm to 17 mm with a mean of 11.4 mm and a standard deviation of 2.7 mm. Median distance was 11.3 mm with an IQR from 9.3 mm to 14.2 mm.

Primary Descriptive Analysis: Femur

Parameter	Mean (Standard Deviation)	Median (Inter- Quartile Range)
Epicondylar Width	79.7mm (3.9mm)	80mm (76.3mm- 83.4mm)
Lateral Condyle AP Depth	62.6mm (3.3 mm)	63.7mm (59.3mm- 65mm)
Femoral Intercondylar Notch Width	19mm (2.3mm)	19.4mm (16.4mm- 20.8mm)
Femoral Intercondylar Notch Height	28.1mm (3.6mm)	28.9mm (26.7mm- 30mm)
Length of Femoral Footprint	17.6mm (1.9mm)	17.7mm (16.2mm- 19.3mm)
Width of Femoral Footprint	10.6mm (1.3mm)	10.5mm (9.6mm- 11.4mm)
Posterior Cartilage to Centre of Whole Footprint	8.8mm (2mm)	9m (7.8mm- 10mm)
Posterior Cartilage to Centre of AM bundle	5.8mm (1.6mm)	5.3mm (4.6mm- 6.6mm)
Posterior Cartilage to Centre of PL bundle	11.3mm (2.4mm)	11mm (10.3mm- 12.5mm)
Inferior Cartilage to Centre of Whole Footprint	7.6mm (2.3mm)	7.9mm (6.4mm- 9.4mm)
Inferior Cartilage to Centre of AM bundle	6.6mm (2.2mm)	7.1mm (4.8mm- 8.5mm)
Inferior Cartilage to Centre of PL bundle	8.2mm (2.9mm)	8.2mm (6.5mm- 10mm)

Primary Descriptive Analysis: Femur

Parameter	Mean (Standard Deviation)	Median (Inter- Quartile Range)
Area of Femoral Footprint- Whole	132.2mm^2 (25.6mm^2)	124.9mm^2 (111.6mm^2- 154mm^2)
Area of Femoral Footprint- AM	63.4mm^2 (13.4mm^2)	63mm^2 (52.2mm^2- 73.5mm^2)
Area of Femoral Footprint- PL	68.8mm^2 (14.1mm^2)	67.3mm^2 (57.7mm^2- 75mm^2)
% Shallowness of Centre of Footprint from Posterior Border- Whole	34% (4.9%)	33.1% (30.1%- 37.9%)
% Shallowness of Centre of Footprint from Posterior Border- AM bundle	26.6% (5%)	26.6% (22.7%- 31.2%)
% Shallowness of Centre of Footprint from Posterior Border- PL bundle	41.4% (5.1%)	40.2% (37.4%- 45.7%)
% Height of Centre of Footprint from Inferior Border- Whole	62.9% (4.8%)	63.7% (60.2%- 66.4%)
% Height of Centre of Footprint from Inferior Border- AM bundle	74.6% (5.8%)	76.1% (71.2%- 79%)
% Height of Centre of Footprint from Inferior Border- PL bundle	50% (5.5%)	50.5% (48.4%- 54%)

Primary Descriptive Analysis- Femur

Parameter	Mean (Standard Deviation)	Median (Inter- Quartile Range)
Diameter of Best- fit Circle in the Footprint- AM bundle	7.4mm (0.9mm)	7.4mm (6.8mm- 8.1mm)
Diameter of Best- fit Circle in the Footprint- PL bundle	7.9mm (0.9mm)	7.5mm (7.3mm- 8.6mm)

- **Epicondylar Width:** The epicondylar width was considered as an independent variable representing the size of the femur. It ranged from 72.4 mm to 86.4 mm with a mean of 79.7 mm and a standard deviation of 3.9 mm. The median was 80mm with an Inter-quartile Range from 76.3 mm to 83.4 mm.
- **Lateral Condyle Depth:** The depth of the lateral condyle was considered as the second independent variable representing the size of the femur. It ranged from 55 mm to 67 mm with a mean of 62.6 mm and a standard deviation of 3.3 mm. The median was 63.7 mm with an Inter-quartile Range from 59.3 mm to 65 mm.
- **Intercondylar Notch Width:** The intercondylar notch width was considered as the third independent variable representing the size of the femur. It ranged from 15.5 mm to 23 mm with a mean of 19 mm and a standard deviation of 2.3 mm. The median was 19.4 mm with an Inter-quartile Range from 16.4 mm to 20.8 mm.

- **Intercondylar Notch Height:** The intercondylar notch height was considered as the fourth independent variable representing the size of the femur. It ranged from 19.5 mm to 33.5 mm with a mean of 28.1 mm and a standard deviation of 3.6 mm. The median was 28.9 mm with an Inter-quartile Range from 26.7 mm to 30 mm.
- **The Length of the Femoral Footprint:** The length of the femoral footprint was found to range from 14.2 mm to 21.2 mm. The mean of the readings was 17.6 mm with a standard deviation of 1.9 mm. The median was 17.7 mm with an Inter- quartile range from 16.2 mm to 19.3 mm.
- **The Width of the Femoral Footprint:** The width of the femoral footprint ranged from 8.3 mm to 14 mm. The mean calculated was 10.6 mm with a standard deviation of 1.3 mm. The median fell at 10.5 mm with the inter-quartile ranging from 9.6 mm to 11.4 mm.
- **The Distance of the Centre of the Whole Ligament from the Posterior Articular Cartilage Border:** The measurement of this distance ranged from 5.2 mm to 12.8mm. The mean was 8.8 mm with a standard deviation of 1.9 mm. The median was calculated to be 9 mm, with an inter- quartile range of 7.8 mm to 10 mm.
- **The Distance of the Centre of the AM Bundle from the Posterior Articular Cartilage:** This distance ranged from 2.7 mm to 9.5 mm with a mean of 5.8

mm and a standard deviation of 1.6 mm. The median was 5.3 mm with the inter- quartile ranging from 4.6 mm to 6.6 mm.

- **The Distance of the Centre of the PL Bundle from the Posterior Articular Cartilage:** The PL bundle was seen to be situated at a range from 6.4 mm to 15.7 mm from the posterior articular cartilage. The mean was 11.3 mm with a standard deviation of 2.4 mm. The median fell at 11 mm with an IQR from 10.3 mm to 12.5 mm.
- **The Distance of the Centre of the Whole Footprint from the Inferior Articular Cartilage:** This distance was observed to range from 2.4 mm to 11 mm. The mean calculated was 7.6 mm with a standard deviation of 2.3 mm. The median was observed to fall at 7.9 mm with the inter- quartile ranging from 6.4 mm to 9.4 mm.
- **The Distance from the Centre of the AM Bundle to the Inferior Articular Cartilage:** The centre of the AM bundle was found superior to the inferior cartilage by a distance ranging from 6.4 mm to 13.7 mm, with mean distance 6.6 mm and a standard deviation of 2.2 mm. The median was 7.1 mm with an IQR of 4.8 mm to 8.5 mm.

- **The Distance from the Centre of the PL bundle to the Inferior Cartilage:** This distance was observed to range from 2.5 mm to 13.7 mm. The mean was observed to be 5 mm with a standard deviation of 1.4 mm. The median interval fell at 4.7mm with the inter- quartile ranging from 4 mm to 6.2 mm.
- **The Area of the Whole Femoral Footprint:** The area of the whole femoral footprint ranged from 100.9 mm^2 to 189.5 mm^2 with a mean area of 132.2 mm^2 and a standard deviation of 25.6 mm^2. The median area fell at 124.9 mm^2 and had an inter- quartile range from 111.6 mm^2 to 153.9 mm^2.
- **The Area of the AM Bundle:** The AM bundle was found to occupy an area on the lateral femoral condyle ranging from 44 mm^2 to 94.6 mm^2. The mean area of the AM footprint was observed to be 63.4 mm^2 with a standard deviation of 13.4 mm^2. The median was 62. 9 mm^2 with an IQR from 52.2 mm^2 to 73.5 mm^2.
- **The Area of the PL Bundle:** The area occupied by the PL bundle was observed to range from 44.8 mm^2 to 98 mm^2. The mean area occupied was 68.8 mm^2 with a standard deviation of 14.1 mm^2. The median was 67.3 mm^2 with an IQR from 57.7 mm^2 to 75 mm^2.

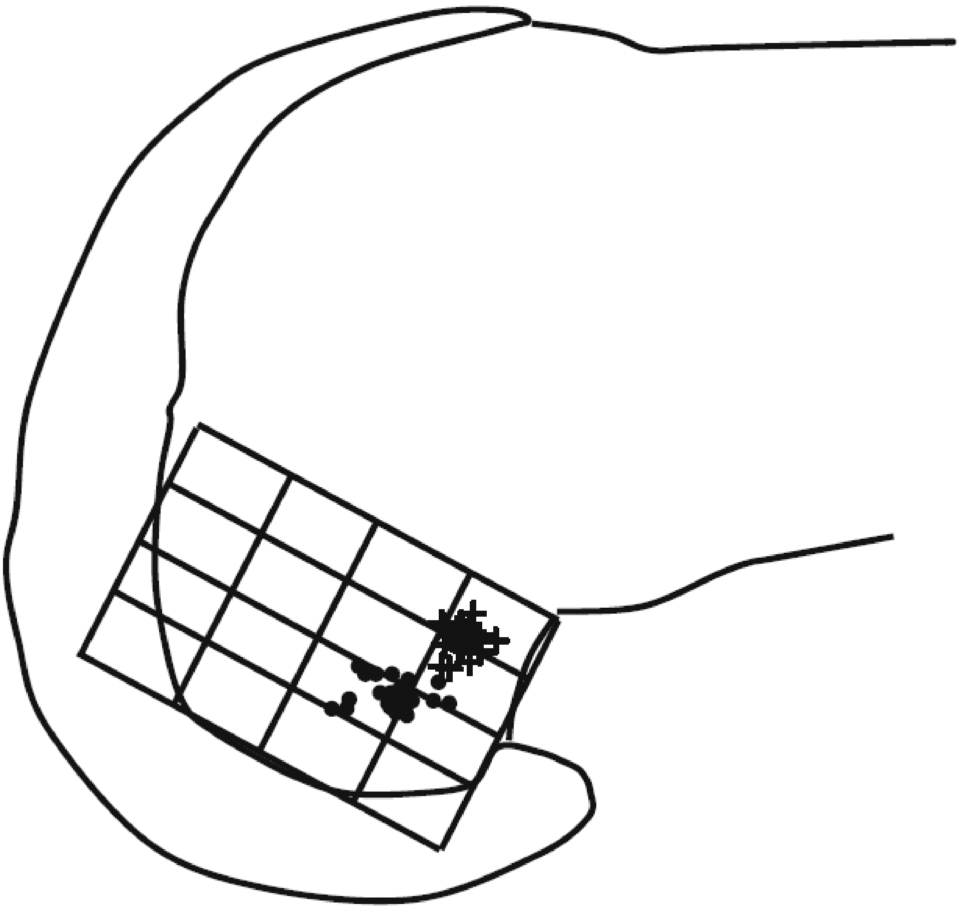
- **Percentage Shallowness of Centre of the Whole Footprint from the Posterior Condylar Reference:** The centre of the femoral footprint as a whole was observed to lie at a range from 25.3% to 42.6% of the depth of the lateral condyle as measured from the posterior reference. The mean percentage shallowness was 34% with a standard deviation of 4.9%. The median percentage shallowness was 33.1% with an IQR from 30.1% to 37.9%.
- **Percentage Shallowness of the Centre of the AM Bundle from the Posterior Condylar Reference:** The AM bundle as found to range from 19.3% to 37.7% shallow from the posterior condylar reference. The mean was computed to be 26.65% with a standard deviation of 5%. The median shallowness fell at 26.6% with the inter- quartile lying from 22.7% to 31.2%.
- **Percentage Shallowness of the Centre of the PL Bundle from the Posterior Condyle Reference:** The percentage shallowness of the PL bundle from the posterior condyle reference was seen to range from 32.7% to 50.6%. The mean shallowness was 41.4% with a standard deviation of 5.1%. The median fell at 40.2% with an IQR from 37.5% to 45.7%.

- **Percentage Height of Centre of the Whole Footprint from the Inferior Condylar Reference:** The centre of the femoral footprint as a whole was observed to lie at a range from 48.5% to 70.1% of the height of the lateral condyle as measured from the inferior reference. The mean percentage height was 62.9% with a standard deviation of 4.8%. The median percentage height was 40.2% with an IQR from 37.5% to 45.7%.
- **Percentage Height of the Centre of the AM Bundle from the Inferior Condylar Reference:** The AM bundle as found to range from 62.4% to 82.5% high from the inferior condylar reference. The mean was computed to be 74.6% with a standard deviation of 5.8%. The median height fell at 76.1% with the inter- quartile lying from 71.2% to 79%.
- **Percentage Height of the Centre of the PL Bundle from the Inferior Condyle Reference:** The percentage height of the PL bundle from the inferior condyle reference was seen to range from 31.5% to 56.8%. The mean height was 50% with a standard deviation of 5.5%. The median fell at 50.5% with an IQR from 48.4% to 54%.
- **Diameters of the Best- fit Circles in the AM Bundle Perimeter:** The diameters of the circles best fitting in the perimeter of the AM bundle ranged from 5.7 mm to 9.1 mm with a mean of 7.4 mm and a standard deviation of 0.9 mm.

The median fell at 7.4 mm with the inter- quartile ranging from 6.8 mm to 8.1 mm.

- **Diameters of the Best- fit Circles in the PL Bundle Perimeter:** These diameters ranged from 5.8 mm to 9.8 mm. The mean diameter was 7.9 mm with a standard deviation of 0.9 mm. The median fell at 7.6 mm with an IQR from 7.3 mm to 8.6 mm.

- **Position of the Centre of the AM and PL bundle footprints on the Modified Amis Measurement Grid (Qualitative):**



+- AM bundle centre **•- PL bundle centre**

Comparison between the Areas of the Femoral and Tibial Footprints

- **The Whole Footprint:** The ratio of the area of the whole femoral footprint to the area of the whole tibial footprint ranged from 0.4 to 1.2. The mean ratio was 0.8 with a standard deviation of 0.2. The median ratio fell at 0.8 with the IQR between 0.69 and 0.85.
- **The AM Bundle:** The area of the femoral AM bundle footprint ranged from 0.4 to 1.1 times the area of the tibial AM bundle footprint. The mean ratio was 0.7 with a standard deviation of 0.1. The median ratio was found to be 0.7 with an IQR from 0.55 to 0.76.
- **The PL Bundle:** The ratio of the area of the femoral PL bundle footprint to that of the tibial PL bundle footprint ranged from 0.5 to 1.4. The mean ratio was observed to be 0.9 with a standard deviation of 0.2. The median fell at 0.9 with an IQR from 0.8 to 1.

Analysis: Tibia

To test the correlation between the location and the area of the footprints of the ACL and the size of the knee, a Carl Pearson Correlation coefficient was applied on the raw data. The following were the inferences:

Pearson Coefficient of the Dependent Variables to the Tibial Plateau Width		
Parameter	**Pearson Coefficient**	**P value**
Length of the Tibial Footprint	0.263	0.238
Width of the Tibial Footprint	0.402	0.064
Whole Footprint Area	0.519*	0.013
Area of the AM Footprint	0.096	0.670
Area of the PL Footprint	.637**	0.001
Posterior Tibial Axis to the Centre of the Whole Footprint	.439*	0.041
Posterior Tibial Axis to the Centre of the AM Bundle	.443*	0.039
Posterior Tibial Axis to the Centre of the PL Bundle	0.250	0.261
Anterior Tibial Border to the Centre of the Whole Footprint	0.141	0.532
Anterior Tibial Border to the Centre of the AM Bundle	0.135	0.548
Anterior Tibial Border to the Centre of the PL Bundle	0.104	0.646
Lateral Meniscus to Centre of the Whole Footprint	.459*	0.032
Lateral Meniscus to Centre of the AM Bundle	.463*	0.030
Lateral Meniscus to Centre of the PL Bundle	0.219	0.327
Medial Tibial Spine to the Centre of the Whole Footprint	.432*	0.045

Pearson Coefficient of the Dependent Variables to the Tibial Plateau Width		
Parameter	**Pearson Coefficient**	**P value**
Medial Tibial Spine to the Centre of the AM Bundle	.448*	0.037
Medial Tibial Spine to the Centre of the PL Bundle	0.042	0.854
Transverse Interspinous Ridge to Centre of the Whole Footprint	0.033	0.882
Transverse Interspinous Ridge to Centre of the AM Bundle	0.100	0.658
Transverse Interspinous Ridge to Centre of the PL Bundle	0.232	0.298
Anterior Extent of PCL to Centre of the Whole Footprint	0.227	0.309
Anterior Extent of PCL to Centre of the AM Bundle	0.393	0.070
Anterior Extent of PCL to Centre of the PL Bundle	0.207	0.355

*Good Correlation

**Strong Correlation

***Very Strong Correlation

Pearson Coefficient of the Dependent Variables to the Tibial Plateau Depth		
Parameter	Pearson Coefficient	P value
Length of the Tibial Footprint	-0.208	0.354
Width of the Tibial Footprint	0.002	0.993
Whole Footprint Area	0.309	0.162
Area of the AM Footprint	-0.121	0.593
Area of the PL Footprint	.529*	0.011
Posterior Tibial Axis to the Centre of the Whole Footprint	.557**	0.007
Posterior Tibial Axis to the Centre of the AM Bundle	.539**	0.010
Posterior Tibial Axis to the Centre of the PL Bundle	.622**	0.002
Anterior Tibial Border to the Centre of the Whole Footprint	.452*	0.035
Anterior Tibial Border to the Centre of the AM Bundle	.560**	0.007
Anterior Tibial Border to the Centre of the PL Bundle	0.341	0.121
Lateral Meniscus to Centre of the Whole Footprint	0.275	0.215
Lateral Meniscus to Centre of the AM Bundle	0.186	0.408
Lateral Meniscus to Centre of the PL Bundle	0.200	0.371
Medial Tibial Spine to the Centre of the Whole Footprint	0.229	0.306
Medial Tibial Spine to the Centre of the AM Bundle	0.298	0.178
Medial Tibial Spine to the Centre of the PL Bundle	-0.199	0.374
Transverse Interspinous Ridge to Centre of the Whole Footprint	-0.087	0.700
Transverse Interspinous Ridge to Centre of the AM Bundle	-0.199	0.375

Pearson Coefficient of the Dependent Variables to the Tibial Plateau Depth		
Parameter	**Pearson Coefficient**	**P value**
Transverse Interspinous Ridge to Centre of the PL Bundle	-0.024	0.916
Anterior Extent of PCL to Centre of the Whole Footprint	0.032	0.889
Anterior Extent of PCL to Centre of the AM Bundle	0.024	0.914
Anterior Extent of PCL to Centre of the PL Bundle	0.215	0.336

*Good Correlation

**Strong Correlation

***Very Strong Correlation

Pearson Coefficient of the Dependent Variables to the Distance of the Transverse Interspinous Ridge from the Posterior Tibial Axis		
Parameter	Pearson Coefficient	P value
Length of the Tibial Footprint	-0.198	0.378
Width of the Tibial Footprint	-0.043	0.851
Whole Footprint Area	0.048	0.830
Area of the AM Footprint	-0.154	0.494
Area of the PL Footprint	0.171	0.448
Posterior Tibial Axis to the Centre of the Whole Footprint	.709**	0.000
Posterior Tibial Axis to the Centre of the AM Bundle	.694**	0.000
Posterior Tibial Axis to the Centre of the PL Bundle	.821**	0.000
Anterior Tibial Border to the Centre of the Whole Footprint	0.075	0.742
Anterior Tibial Border to the Centre of the AM Bundle	0.217	0.332
Anterior Tibial Border to the Centre of the PL Bundle	0.014	0.949
Lateral Meniscus to Centre of the Whole Footprint	0.098	0.663
Lateral Meniscus to Centre of the AM Bundle	0.096	0.669
Lateral Meniscus to Centre of the PL Bundle	0.071	0.755
Medial Tibial Spine to the Centre of the Whole Footprint	0.416	0.054
Medial Tibial Spine to the Centre of the AM Bundle	.426*	0.048
Medial Tibial Spine to the Centre of the PL Bundle	-0.091	0.686
Transverse Interspinous Ridge to Centre of the Whole Footprint	-0.023	0.920

Pearson Coefficient of the Dependent Variables to the Distance of the Transverse Interspinous Ridge from the Posterior Tibial Axis		
Parameter	**Pearson Coefficient**	**P value**
Transverse Interspinous Ridge to Centre of the AM Bundle	-0.174	0.439
Transverse Interspinous Ridge to Centre of the PL Bundle	-0.022	0.923
Anterior Extent of PCL to Centre of the Whole Footprint	0.154	0.495
Anterior Extent of PCL to Centre of the AM Bundle	0.173	0.441
Anterior Extent of PCL to Centre of the PL Bundle	0.256	0.249

*Good Correlation

**Strong Correlation

***Very Strong Correlation

Hence, the dependent variables correlating well with the size of the knee, as shown above, were:

- Whole Footprint Area
- Area of the PL Footprint
- Posterior Tibial Axis to the Centre of the Whole Footprint
- Posterior Tibial Axis to the Centre of the AM Bundle
- Posterior Tibial Axis to the Centre of the PL Bundle
- Anterior Tibial Border to the Centre of the Whole Footprint
- Anterior Tibial Border to the Centre of the AM Bundle
- Lateral Meniscus to Centre of the Whole Footprint
- Lateral Meniscus to Centre of the AM Bundle
- Medial Tibial Spine to the Centre of the Whole Footprint
- Medial Tibial Spine to the Centre of the AM Bundle

Discussion

A thorough understanding of the native ACL attachment anatomy is absolutely essential for a successful ACL reconstruction surgery[67]. The success rates of the surgery worldwide have been reported to range from 69% to 95%[13, 68-70]. Long term studies show the recurrence of symptoms and need for revision surgery[71-73]. These poor outcomes can be attributed in a major part to the poor placement of the ACL tunnels. Worldwide, almost 10% to 40% tunnels have been reported to be placed wrongly. With the advent of the double bundle ACL reconstruction which in essence recreates the complex anatomy and biomechanics of the native ACL, leaving a very narrow margin for error, it is even more necessary to thoroughly research the anatomy of the ACL[74, 75].

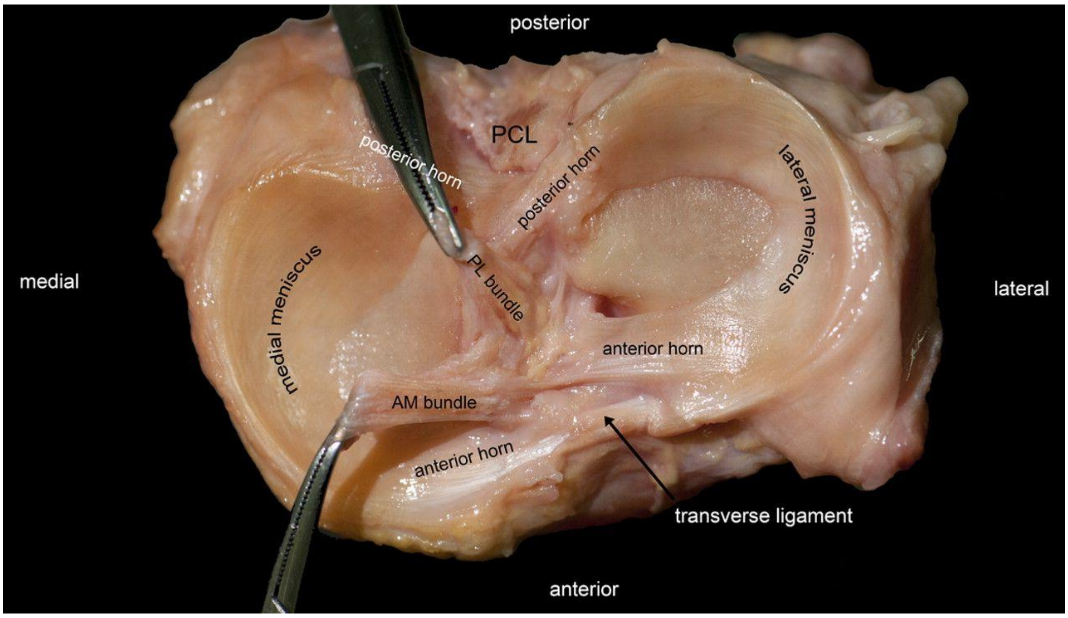
Several authors[76-79] have demonstrated in early follow- up prospective studies that the double bundle ACL reconstruction gives a much more rotationally stable knee post operatively than a single bundle ACL reconstruction, without compromising on the anterior translational stability or functional outcome. Jarvela et al[80] reported in a 14 month follow- up randomised controlled trial between single bundle and double bundle ACL reconstructions that the double bundle group had a significantly better rotational stability and the same antero- posterior stability as the single bundle group on the Lysholm and IKDC scores. Xu et al[81] did a meta- analysis of all the trials and showed the same result. Yagi et al[45] observed that with a double bundle ACL reconstruction, rotatory loading was better tolerated than a single bundle ACL reconstruction.

Previous authors have variously proposed reference points for the accurate placement of the tibial tunnels for the single bundle ACL reconstruction.

As in our study, the measurement from the posterior tibial axis consistently gave a similar position of the ACL footprint centre in the sagittal plane in most studies[8, 12, 14, 82].

Howell[82] propounded the placement of the tibial tunnel using the roof of the intercondylar notch as a guideline. Hutchinson and Bae[83] were the first to propose an 'Over- the- back position with the anterior aspect of the PCL as a reference. Edwards et al[8] used only the bony landmarks to guide the tibial tunnel placement.

There are various 'point and shoot' drill guides available in the market which employ the surgeon's judgment and expertise for the placement of the tibial tunnels. Our belief is that the placement of the tibial tunnel will be much more accurate if these are combined with a ruler, or are converted to contoured jigs using one or more landmarks as given in this study.



For a landmark to be used as a reference point, it has to be consistent in its position, readily accessible and easily recognizable with arthroscopy, and must yield accurate and reproducible measurements. The posterior tibial axis, although the most consistent of all the landmarks in most of the studies including ours and having the best correlation with the size of the knee, is unfortunately not an arthroscopic landmark. But it can be used as a guideline in development of software for future **computer navigated surgery[84]** in South India.

Takahashi et al[85] observed the bundle centres to lie between 29% and 32% of the AP depth of the tibial plateau. Staubli and Rauschning[12], in a study of cryosections, found the overall centre to lie around 43%. Edwards et al[8] found the overall attachment centre to lie around 36% and the bundle centres to lie at 29% and 46% respectively. In our study, we found the overall centre to lie at 43%. The AM bundle was at 34.2% while the PL bundle was at 47.1%.

Measurements from the anterior border of the tibia also had similar consistency and correlation, but there still exists some confusion in the very definition of the anterior border of the tibia and it is also not arthroscopically clearly identifiable. Similar problems affected the anterior landmarks as defined by Takahashi et al[85]. It was not easy to measure in the sagittal plane from the medial tibial spine as the exact AP position of its summit was not easily identifiable, as has been reported previously[83].

When locating the ACL from the interspinous ‘over- the- back ridge, the measurements were consistent and showed a small standard deviation. Hutchinson and Bae[83] first described this ‘Over- the – back’ position and the anterior extent of the PCL as the most reliable and accurate reference. Later studies by Edwards et al[8] and Colombet et al[15]. Colombet[15]found the interspinous ridge, which they called the “retro- eminence ridge” their most useful landmark. They found medio- lateral orientation of the bundle attachments in all their specimens, but they described the centres of the bundles according to the ‘parallel projections’ of the fibres and not actual centres of the footprints. Edwards et al[8] found a wide variation in the orientations of the bundle attachmens with respect to each other.

Morgan et al[86] proposed a method of referencing from the most anterior part of the PCL. I this study, instead of using a deformable structure like the PCL, we have used the anterior extent of the attachment of the PCL, which is usually palpable with an arthroscopic probe just posterior to the interspinous ridge.

The Bundles- Chhabra et al[87] published arthroscopic, X- ray and cadaveric proof that the AM and PL bundles exist separately and are identifiable even in the adult. Ferretti[23] also supported this view. However, in our study, we did not find the bundles to be explicitly demarcated structurally. We found a more functional division as the anterior and posterior fibres became differentially tense across the range of motion. Edwards et al[8] had a similar experience.

The length and width of the ACL attachment correlated well with previously published data.[8, 25]

For the drilling of tibial tunnels, it has been shown that too anteriorly placed tunnels have the potential for the intercondylar notch to impinge upon the graft. This can lead to ‘capturing’ of the knee causing extension deficit or graft laceration[16, 82] and the formation of a ‘cyclops’[88]. Ikeda et al[89] reported that an anteriorly placed tunnel also causes an incomplete correction of the antero- posterior instability, which is the main aim of the surgery. Hence, we have presented our data taking our projected tunnels as close, tending posteriorly, to the actual centres of the bundle attachments as possible.

Edwards et al[8] considered their tunnels as posterior as possible within the bundle attachments. This may be a safer approach. But they reported that the centres of their tunnels were actually only within 1mm of the centres of the footprints, thus highlighting the miniscule margin for error.

We have used several measurement systems for the location of the femoral attachment, reflecting the methods published previously. Some of them may be directly useful for the surgeon, while others may be used for anatomic purposes and in the future, as baseline input data for computer assisted surgery. Some methods were described more in pertinence to arthroscopy.

As in the tibia, accurate femoral tunnel placement too is essential to improve the outcome of the ACL reconstruction surgery[16]. Sommer et al[90] found a significant correlation between the femoral tunnel placement and the post-operative International Knee Documentation Committee Score (IKDC). The IKDC score was inversely related to the distance of the graft tunnel from the most ‘isometric’ point as seen on X- ray. It is just as important to recreate the anatomy of the femoral attachment and hence, the biomechanics of the ACL in a double bundle ACL reconstruction. Mae et al[91], using biomechanical analysis with a robotic simulator, found out that when 2 femoral sockets are used, the antero- posterior as well as rotational stability is better than a single femoral socket. Mommersteeg et al[92] studied in detail the fibre bundle anatomy and suggested that a complete ACL reconstruction per se may not be achieved by recreating a single fibre bundle.

With increasing interest in the double bundle anatomic ACL reconstruction, it has become imperative to accurately map out the attachment of the ACL and define well the attachments of the individual bundles. Outcome studies presenting results of such anatomic reconstructions are also the need of the hour.

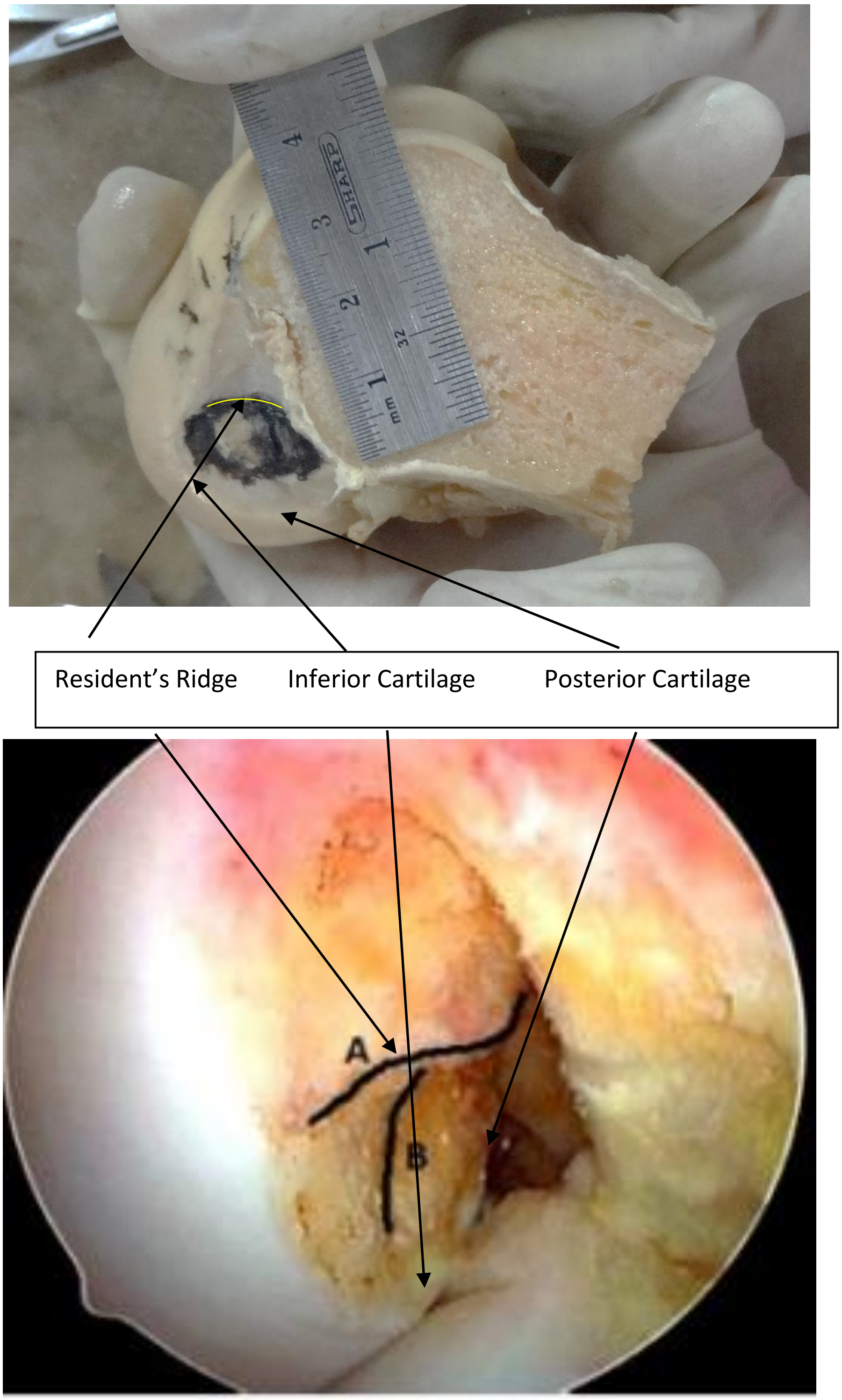
We have applied a number of techniques to describe the femoral footprint which have been described in previous papers in order to obtain most information. Bernard et al[27] described a radiographic method of plotting 'quadrants' on true lateral radiographs of the distal femur.

Amis et al[14] devised a method of plotting a circle on a photograph of the cadaveric distal femur with the posterior border as its arc and described the attachment as 'shallow' or 'deep' and 'high' or 'low' in relation to the quadrants of this circle. Klos et al[93] applied this method to the lateral radiograph of the distal femur to make the method more useful clinically. Edwards et al[9] devised a method to make use of this posterior condyle referencing circle in arthroscopy.

They considered the arthroscopically visible posterior border of the intercondylar notch as the arc of the Amis circle and plotted the ‘quadrants’ on the medial aspect of the lateral intercondylar notch. We have used the method described by Edwards in our study. Our results are similar to those described by Edwards et al. This method in our study yielded very small standard deviations of approximately 2mm, especially in the ‘high- low’ axis. The readings correlated well with the posterior condyle referencing diameter.

We have used the distance of the centre of the footprint from the posterior and inferior articular cartilage margin as a variable for the accurate location of the femoral footprint. These parameters are useful in that they can be easily measured during arthroscopy using a ruler. These mean distances can be combined with the percentage depth and height to estimate the location of the projected tunnels.

More accurate tunnels can be placed by combining more than one parameter measured in this study and matching them and cross checking the position of the tunnels.


Resident's Ridge
Inferior Cartilage
Posterior Cartilage
A
B

The popular clock face reference parameters were not considered by us as a variable because as Edwards et al[9] pointed out, the clock face measurements differed when considered parallel to the long axis of the femur or parallel to the roof of the intercondylar notch. Edwards et al[9] used the posterior outlet of the notch as the reference for the clock face as the anterior inlet may not be circular and the attachment of the ACL is nearer to the posterior outlet than to the anterior inlet. They have proposed that the clock face measurements need to be assessed carefully in varying degrees of flexion of the knee to get the exact assessment.

The modified Amis measurement grid method attempted to extrapolate the qualitative information collected from the cadaveric study into arthroscopically familiar zones. The 'quadrants' as described by Bernard[27] were plotted on the lateral wall of the intercondylar notch. Edwards et al[9] observed the AM bundle to lie at 11 o'clock and 5 mm anterior to the posterior cartilage margin and the PL bundle to lie 9 mm from the outlet at 10 o'clock. Mochizuki et al[94] observed the AM bundle to lie at 6 mm in front of the outlet at 1:40 o'clock and the PL bundle at 9 mm at 3:10 o'clock, parallel to the roof of the intercondylar notch. At these positions, they were at 28% and 60% shallow respectively. Takahashi et al[85] found the bundles at 23% and 25% shallow respectively from the posterior outlet. Yasuda et al[10] observed the AM bundle as being 5-6 mm shallow and at 10:30 o'clock.

Other reports have placed the AM and PL bundles as 7 mm and 5 mm diameter[95] and both as 4.5 mm tunnels[10]

The variables were not found to correlate significantly with each other.

Future developments may use computer navigation as an important tool for ACL surgery. This method relies on multiple aspects of qualitative and quantitative information to accurately map out the footprints of the ACL as a whole and as that of the 2 bundles in relation to the accurately registered size and contour of the knee. It will be an important tool in giving more satisfactory results of ACL reconstruction surgery. We think that the qualitative and quantitative data presented in this study may be useful for the software database for the South Indian population.

In our experience with this study, the advantage of working in vitro was that we could carry out easy and accurate measurements directly.

Conclusion

❖ We have obtained the following descriptive data from our study:

Parameter	Mean (Standard Deviation)
Tibial Plateau Width	75.6mm (4.3mm)
Tibial Plateau Depth	46.7mm (3.8mm)
Transverse Interspinous ridge-Posterior Tibial Axis	15.8mm (3mm)
AP Diameter of footprint	19.6mm (1.5mm)
ML Width of footprint	11mm (1.7mm)
Area- Whole footprint	172.5mm^2 (27.5mm^2)
Area- AM bundle	95.8mm^2 (15.7mm^2)
Area- PL bundle	75.5mm^2 (17mm^2)
Posterior Tibial Axis to Centre of footprint	26.6mm (3.7mm)
Posterior Tibial Axis to Centre of AM bundle	30.7mm (4.1mm)
Posterior Tibial Axis to Centre of PL bundle	21.6mm (4mm)
Anterior Tibial Border to Centre of footprint	22mm (3.3mm)
Anterior Tibial Border to Centre of AM bundle	18.1mm (3.8mm)
Anterior Tibial Border to Centre of PL bundle	26.5mm (3.2mm)
Distance Medial from the Lateral Meniscus- Whole footprint	11.9mm (2.5mm)
Distance Medial from the Lateral Meniscus- AM bundle	12.1mm (2.5mm)

Parameter	Mean (Standard Deviation)
Distance Medial from the Lateral Meniscus- PL bundle	13.3mm (3.4mm)
Distance Lateral from the Medial Tibial Spine- Whole footprint	8mm (2.5mm)
Distance Lateral from the Medial Tibial Spine- AM bundle	9.3mm (2.7mm)
Distance Lateral from the Medial Tibial Spine- PL bundle	8.6mm (2mm)
Distance Anterior from Transverse Interspinous Ridge- Whole footprint	12.7mm (2.9mm)
Distance Anterior from Transverse Interspinous Ridge- AM bundle	16.9mm (3.1mm)
Distance Anterior from Transverse Interspinous Ridge- PL bundle	8mm (2.8mm)
Distance Anterior from the PCL- Whole footprint	16mm (2.7mm)
Distance Anterior from the PCL- AM bundle	19.5mm (3.5mm)
Distance Anterior from the PCL- PL bundle	11.4mm (2.7mm)

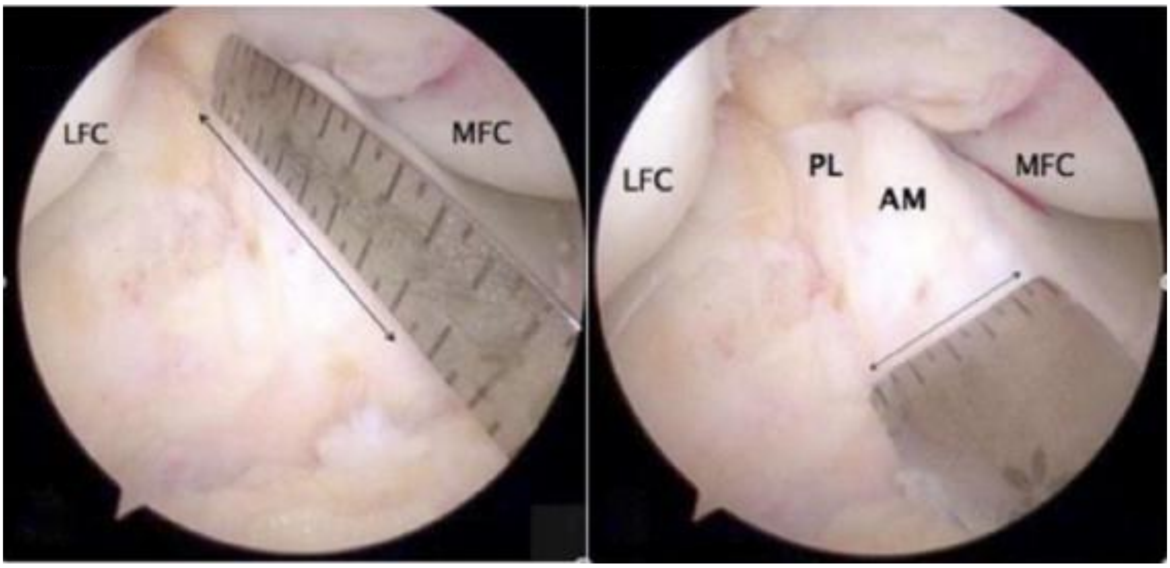
Parameter	Mean (Standard Deviation)
Epicondylar Width	79.7mm (3.9mm)
Lateral Condyle AP Depth	62.6mm (3.3 mm)
Femoral Intercondylar Notch Width	19mm (2.3mm)
Femoral Intercondylar Notch Height	28.1mm (3.6mm)
Length of Femoral Footprint	17.6mm (1.9mm)
Width of Femoral Footprint	10.6mm (1.3mm)
Posterior Cartilage to Centre of Whole Footprint	8.8mm (2mm)
Posterior Cartilage to Centre of AM bundle	5.8mm (1.6mm)
Posterior Cartilage to Centre of PL bundle	11.3mm (2.4mm)
Inferior Cartilage to Centre of Whole Footprint	7.6mm (2.3mm)
Inferior Cartilage to Centre of AM bundle	6.6mm (2.2mm)
Inferior Cartilage to Centre of PL bundle	8.2mm (2.9mm)
Area of Femoral Footprint- Whole	132.2mm^2 (25.6mm^2)
Area of Femoral Footprint- AM	63.4mm^2 (13.4mm^2)
Area of Femoral Footprint- PL	68.8mm^2 (14.1mm^2)
% Shallowness of Centre of Footprint from Posterior Border- Whole	34% (4.9%)
% Shallowness of Centre of Footprint from Posterior Border- AM bundle	26.6% (5%)
% Shallowness of Centre of Footprint from Posterior Border- PL bundle	41.4% (5.1%)
% Height of Centre of Footprint from Inferior Border- Whole	62.9% (4.8%)

Parameter	Mean (Standard Deviation)
% Height of Centre of Footprint from Inferior Border- AM bundle	74.6% (5.8%)
% Height of Centre of Footprint from Inferior Border- PL bundle	50% (5.5%)

- We have inferred from this study that the **intra- articular landmarks** on the tibial plateau are a good initial point for the accurate location and placement of the tibial tunnel for both a single bundle and a double bundle ACL reconstruction. Since the distances of the centres of the footprint and the bundles from arthroscopic landmarks like the transverse interspinous ridge, the PCL, the medial tibial spine, the anterior root of the lateral meniscus have very small standard deviations, we propose that they will remain approximately **constant**, over a large range of the **size of the knee**. This is apparent in this study by our observations being within the limit of error of studies performed in East Asia and the Western World. Hence, they are the most precise means to locate the centres. Moreover, they are located in and around the centre of the tibial plateau, making them **easily accessible** by arthroscopy.
- We have also presented useful data for the location and diameter of tunnel placement for the footprint for the femoral socket for ACL reconstruction. The distance of the centres of the footprint and the bundles from the posterior articular cartilage, the inferior articular cartilage and the centre of

the intercondylar ridge can be useful guidelines for tunnel placement in the South Indian ACL patient.

- The use of this data, aided especially by an **Arthroscopic Ruler** or **adjustable guides** designed to reference from these landmarks, could be a remarkably useful method of consistently locating the tibial footprint. Considering the results of this study and observing the constancy of the relations of the landmarks, we encourage the arthroscopic surgeon to have the arthroscopic ruler as an important part of the ACL armamentarium.



- We have given several parameters which correlate well to the size of the knee. The best correlation for location of the tibial footprint was seen to be with its **distance from the posterior tibial axis**. The best correlation for the femoral footprint was found to be with the **posterior condyle circle referencing**. Unfortunately, these measurements are not possible arthroscopically. But they may be very useful in the future as baseline references for **Computer Navigated ACL Reconstruction** in South Indian patients.

Similarities and Differences found with similar studies in the Western population:

- The mean South Indian knee was found to be about 95% of the mean Western knee in width and about 90% of it in depth.
- Inspite of this difference in the size of the knee, the area of the tibial and femoral footprints did not exhibit a significant difference.
- In the tibia,
  - The distances from the anterior intra- articular landmarks (Root of the lateral meniscus, apex of the medial tibial spine) did not exhibit significant differences from the Western population
  - The mean distance from the transverse intercondylar 'Over- the- back ridge in South Indian knees was 84.6% of that of the mean Western knee.
  - The mean distance from the anterior extent of the PCL was 86% of that of the Western knee.
- In the femur,
  - The location of the femoral footprint and the bundles was not significantly different than the Western Population.
  - The area of the footprint was also not significantly different from the Western knees.

Potential Limitations of Our Study

- Observer Errors: Minimization of these errors has been attempted with all the observations taken by a single observer.
- Instrument errors: A single set of certified, well calibrated instruments was used throughout the study for all the 22 samples to minimize instrument errors.
- Alterations of the knee with age: Wherever possible, young cadavers were preferred over aged ones. However, the authors are not aware of any observations suggesting that the attachments of the ACL undergo alterations with aging.
- The femoral AM footprint: The femoral AM footprint lies higher in the notch in a plane at an angle to that of the PL footprint. Hence, its analysis may not be accurately possible in an otherwise highly accurate 2- dimensional image processing software. More 3 dimensional topographic studies are required to accurately map the AM bundle footprint.

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Annexures

PROFORMA

Serial no.:

Side:

A) Tibia:

- **vii) Tibial Plateau Width (mm):**
- **viii) Tibial Plateau Depth (mm):**
- **ix) Distance of transverse interspinous 'Over the back ridge' from posterior tibial axis (mm):**
- **x) Tibial footprint pattern (mm):**
- **xi) Tibial Footprint AP diameter (mm):**
- **xii) Tibial footprint ML width (mm):**
- **xiii) Area of footprint (bundles and as a whole) (mm^2):**
  Whole: AM: PL:

- **xiv) Distance of centres of bundles and whole footprint respectively from:**

	Whole	AM	PL
g) Posterior tibial axis (mm):			
h) Anterior tibial border (mm):			
i) Posterior border of the anterior horn of Lateral meniscus (mm):			
j) Medial tibial spine apex:			
k) Transverse Inter- spinous 'Over the back' ridge (mm):			
l) Anterior extent of PCL			

B) Femur:

- **v) Epicondyar Width (mm): AP diameter of lateral condyle (mm):**
- **vi) Femoral Inter- condylar Notch diameter (mm):**
- **vii) Femoral Inter- condylar Notch height (mm):**

viii) Measured distance of centres of footprints from:

W AM PL

d) (Arthroscopically) Posterior Articular Cartilage margin:

e) (Arthroscopically) Inferior Articular Cartilage Margin:

f) Intercondylar ridge:

ix) Posterior Lateral Condyle diameter reference (% Shallowness):

W AM PL

x) Posterior Lateral Condyle diameter reference (% height):

W AM PL

xi) Position on (Amis) Measurement grid:

xii) Diameters of best- fit circles: AM PL

xiii) Length of femoral footprint (mm):

xiv) Width of femoral footprint (mm):

xv) Ratio of Areas of femoral to tibial footprints:

W AM PL

xvi) Area of femoral footprint (mm^2): W AM PL

Statistician's Certificate for Sample Size

MIE-13/16/2014/966

1.1.2014

TO

The professor of Orthopaedics,

Kilpauk Medical Colllege Hospital,

Chennai-10

Sub: Optimal sample size for the project– reg.

Dear Sir,

This is regarding the project titled "CADAVERIC MORPHOMETRIC STUDY OF THE ATTACHMENTS OF THE ANTERIOR CRUCIATE LIGAMENT IN SOUTH INDIAN POPULATION".

The primary objectives of the project are

1. To estimate the measure of the area / length of the Tibial and Femoral footprints of the Anterior Cruciate Ligament (As a whole and as Antero – medial and Postero – lateral bundles) in South Indian Population.
2. To describe the anatomical locations of the Tibial and the Femoral foot prints (As a whole and as Antero-medial and Postero-lateral bundles) of the Anterior Cruciate Ligament in South Indian Population.

The secondary objective of the project is

3. To analyse the clinical application of the above measurements for improved tunnel placement and to estimate the requisite graft diameter for ACL reconstruction in South Indian Population.

As per the literature review in terms quantitative research, the optimal sample size has been provided for the primary objectives by considering the maximum mean size and its corresponding details.

Sample size = $(\text{Error})^2 * (\text{Variance}) / (\text{Precision})^2$

$= (1.96)^2 * (4) / (5\% \text{ of } 17)^2$

$=22$

Where Mean = 17 mm; Variance = 4 mm^2 and Relative precision = 5% of Mean = 0.85.

If retrospective, that is selection from line listing (adjusted for 10% loss)

Sample size = 22/0.9

= 25

Thanks with regards

Dr. N. Uthayakumaran.

Technical Officer (Stat.)

National Institute of Epidemiology

Permission Certificate from the Department of Anatomy

12/12/2013

Chennai.

From :
The Professor and Head,
Dept. of Anatomy,
Kilpauk Medical College,
Chennai- 1o.

To,
The Dean,
Kilpauk Medical College,
Chennai- 10.

Respected Sir,

Sub: Permission to Perform Research Study in Dissected Cadavers in the Department of Anatomy

Dr. Pushkar Parag Bhide, pursuing his post- graduation in M. S. (Orthopaedics) in the Department of Orthopaedics, Kilpauk Medical College and Hospital, has planned and proposed a research study titled "**A Cadaveric Morphometric Study of the Attachments of the Anterior Cruciate Ligament in South Indian Population**".

Since there are adequate cadavers in our department at present, I have no objection to him performing said study on the cadavers.

Thanking You,

Yours Sincerely,

V. Preethi Ramya

for PROFESSOR AND HEAD
DEPARTMENT OF ANATOMY
KILPAUK MEDICAL COLLEGE
CHENNAI - 600 010.

Institutional Ethical Committee Approval Certificate

INSTITUTIONAL ETHICAL COMMITTEE
GOVT. KILPAUK MEDICAL COLLEGE
CHENNAI-10
REF.NO.18520/ME-I/Ethics/2013 Dt:05.12.2013
CERTIFICATE OF APPROVAL

The Institutional Ethical Committee of Govt. Kilpauk Medical College, Chennai-10 reviewed and discussed the application for approval "A Study on cadaveric morphometric study of the attachment of the anterior cruciate ligament in south Indian population" – For Project work submitted by Dr.Bhide Pushkar Parag, MS (Ortho) PG Student, KMC / GRH, Chennai.

The Proposal is APPROVED.

The Institutional Ethical Committee expects to be informed about the progress of the study any Adverse Drug Reaction Occuring in the course of the study any change in the protocol and patient information / informed consent and asks to be provided a copy of the final report.

28/1/14

CHAIRMAN
Ethical Committee
Govt. Kilpauk Medical College, Chennai

GOVT. KILPAUK MEDICAL COLLEGE * Kilpauk, Chennai-10. *
2 8 JAN 2014

TIBIA

Sample No.	Side	TPW	TPD	TIR- PTA	TFP- L	TFP- W	Area (sq. mm)		
							Whole	AM	PL
1	Left	77.7	51	15.4	17.5	13.8	120.5693	59.0985	61.4319
2	Right	86.4	48.1	12.8	22.8	14.4	234.5417	101.6517	127.0989
3	Left	69.1	41.3	11	20.8	12.3	193.1161	125.6606	68.2976
4	Left	75.3	48.9	18.7	22.2	11.8	186.4415	114.2039	65.0224
5	Right	79.9	46.7	16.3	19.4	12.6	156.5641	94.2023	63.7144
6	Right	71.9	40	13.3	19	11.5	117.3041	76.2416	44.9043
7	Left	76.6	42.3	10.7	20.4	11.8	176.7364	105.1423	69.0304
8	Left	77.2	43.4	12.5	21.2	10.1	180.2853	99.1175	81.1459
9	Right	72.6	42.8	13.7	17.9	10.5	152.9027	94.5184	59.8279
10	Right	68	43.5	12.8	19.8	9.9	148.4119	80.472	67.8439
11	Right	74.6	46.9	19.6	19.4	10.4	160.1592	88.0247	71.6274
12	Left	70.7	46.7	15.9	18.2	10.7	164.9984	91.9422	75.7387
13	Left	71	49.9	16	17.6	7.5	167.2987	85.5222	81.581
14	Right	74.9	43.9	15.4	19	9.3	170.2208	96.7707	73.2209
15	Right	79.3	52.3	18.2	17.5	9.4	181.6276	93.6139	82.9341
16	Left	77.3	50.5	16.2	20	8.9	204.1387	103.3585	100.888
17	Right	78	46.5	14.7	19	8.6	202.6173	126.8709	72.8398
18	Left	80.3	54	21.7	18.1	12	195.0007	97.6933	95.4967
19	Left	77.3	47.2	18	19.5	12.3	191.057	88.6145	87.791
20	Right	77.3	49.3	19	20.8	11.4	190.136	111.6755	84.131
21	Left	77	48.7	19.7	20.7	11.6	149.54	76.878	71.0286
22	Right	70.9	42.6	15	19.5	11	151.7071	95.8297	61.8376

TPW- Tibial Plateau Width, TPD- Tibial Plateau Depth, TIR- PTA- Transverse Interspinous Ridge to Posterior Tibial Axis, TFP- L- Tibial footprint length, TFP- W- Tibial footprint width, TIBIA- Distances of Centers from anatomical Landmarks

Sample No.	TFP- PTA			TFP- ATB			TFP- LM		
	Whole	AM	PL	Whole	AM	PL	Whole	AM	PL
1	23.2	25	18.6	26.5	27.9	32.3	11	11.5	12.7
2	26.1	30.2	20.4	25.2	18.5	29.6	16.9	17.3	17
3	16	20.3	13.5	23.9	18.8	27.3	11.4	10.5	12.8
4	31.9	37.9	26.9	22.9	18.9	27.3	7.5	10.5	8.7
5	28	32.8	24	21	17.5	20.9	17.5	17.3	16.6
6	24.1	26.4	20.5	15.5	11.9	22.3	6.2	9.3	6.9
7	23.7	28.2	16.4	18.2	12.3	22.5	9.6	11.2	8.2
8	25.5	28.7	16.8	20.5	16.6	26.5	12.3	11	18.1
9	24.6	29.2	16.6	18.9	15.7	24.8	11.7	10.9	16.3
10	23.4	26.5	18.4	24.2	18.2	28.2	11.8	10.4	15.3
11	30.5	33.5	26.4	21.8	18.9	27.1	14.9	13	18.9
12	25	28.8	19.8	22	17.6	26.6	12.7	12.3	13.9
13	27.7	31.4	26.7	26.9	23.3	29.1	12.2	11.6	15.3
14	23.9	29.5	19.1	25.5	20.8	30.6	11.9	11.7	14.2
15	30.5	34.5	25.3	19.6	16.8	25	11.5	13	11.2
16	26.6	33	23	23.8	20	27.2	12.8	11	16.4
17	31.5	35.5	20.6	25.8	21.2	30.8	11.5	11.6	13
18	28.8	32.8	25.5	24.4	21.4	26.8	11.4	8.9	13.9
19	30.6	35.8	26.1	18	13	23.1	13	11.7	15.9
20	25.7	30	21.1	24.3	20.5	29.8	12.3	18.9	12.3
21	30.8	35.7	26.3	18.7	14.6	23.3	11.4	10.7	11.4
22	26	30	23.8	17.3	13.9	21.5	9.1	12.3	7.7

TFP- PTA- Tibial footprint to Posterior Tibial Axis,TFP- ATB- Tibial Footprint to Anterior Tibial Border, TFP- LM- Tibial footprint to Lateral Meniscus

TIBIA- Distances of Centers from anatomical Landmarks

Sample no.	TFP- MTS			TFP- TIR			TFP- PCL		
	Whole	AM	PL	Whole	AM	PL	Whole	AM	PL
1	5	7.5	5.5	12.8	17.8	9.5	16.4	19.9	14.2
2	10.2	14.7	9.7	16.6	20.8	12.6	17.1	22.5	12
3	8	6.4	11	9	13.7	5	11.5	15.8	7.3
4	7.5	10.5	8.7	12.3	15.5	7.4	16.5	18	13.3
5	13.3	6.4	10.9	9.3	13	6	14	16.9	8.4
6	6.2	9.3	6.9	15.4	17.9	10.7	16	19.8	11.2
7	5.7	6.5	9.8	13.7	19.4	9.5	16	20.5	10.8
8	5.4	6.4	9.8	9.1	16.8	7.3	16.3	20.8	10
9	6.5	7.6	10	11.4	16	5	13.3	18.3	7.8
10	6.4	8.2	6.4	13.5	17.2	5.5	16.4	10.9	11.4
11	6.9	9.7	6.9	10.9	13.7	6.4	16.9	20.3	9.7
12	4.6	3.9	12.6	10.9	13.7	7	13.7	16.9	9.8
13	6	7.8	6.6	11.4	13.7	6.7	10.5	15	7.8
14	8.6	10.5	8.6	11.5	15.8	5.5	14.8	19.4	10.5
15	9.5	10.6	8.2	14.5	16.1	9	19	20.7	14.6
16	6.8	9.2	5.5	11.5	16.5	6.4	18	20.8	12.9
17	6.7	9	6.5	12	16.5	7.4	17.3	20.5	12
18	9	11.7	8.8	12.5	16.4	8.3	12.5	16.4	8.3
19	10.9	12.3	8.9	13.2	17.7	8.9	17.7	22.5	14.3
20	12.9	9.1	12.2	11.4	15.7	7.8	18.9	23	14.4
21	10.5	14.6	7.5	14.4	19.6	9.1	18	24.5	14.7
22	10	12.5	8.5	22.6	27.5	17	22.6	27.5	17

TFP- MTS- Tibial footprint to Medial Tibial Spine, TFP- TIR- Tibial Footprint to Transverse Interspinous Ridge, TFP- PCL- Tibial footprint to anterior extent of the PCL

FEMUR

Sample No.	Side	ECW	LCD	INW	INH	FFP- L	FFP- W
1	Left	78.9	62	20	28	18.2	8.7
2	Right	83.8	59.3	16.4	26.4	17.5	8.3
3	Left	72.4	55	20.8	27.5	15.3	9.9
4	Left	82.7	62.8	16.9	28.7	17.9	9.6
5	Right	86.4	66.1	19.9	29.6	16.7	10.5
6	Right	78.9	64.4	16.4	19.5	15.6	9.6
7	Left	81.4	66.4	20.5	28.6	18.5	10.5
8	Left	79.6	62.6	18.5	26.1	21.2	10.5
9	Right	77	65.7	18.9	29.2	17.8	11.3
10	Right	72.9	59.3	16.4	20.3	19.5	12.2
11	Right	75.9	60	22.5	29.3	17.6	11.4
12	Left	76	58.3	15.5	30	15.3	9
13	Left	78.8	64.4	17.8	29.4	14.2	11.4
14	Right	74.6	57.9	23	30	14.5	10
15	Right	83.3	63.5	19.9	28.3	19.2	10.5
16	Left	84.1	65	21.8	33.5	16.4	10.4
17	Right	80.5	64.1	15.7	32.5	19.6	12
18	Left	84.6	65.2	21	31.7	21	9.6
19	Left	81.4	67	20.9	26.8	19.5	12.7
20	Right	83.6	63.9	20.4	32.4	17.1	11.4
21	Left	80.7	65	16.2	22.5	18	14
22	Right	76.4	59.3	18	29.3	16.4	10.6

ECW- Epicondylar Width, LCD- Lateral condyle depth, INW- Intercondylar Notch Width,
INH- Inrecondylar Notch Height, FFP-L- Femoral footprint Length, FFP- W- Femoral footprint Width

FEMUR- Distances of Centers from anatomical Landmarks

Sample No.	FFP- PAC			FFP- IAC			FFP- ICR		
	Whole	AM	PL	Whole	AM	PL	Whole	AM	PL
1	9.1	2.7	11.6	2.4	2.4	2.5	10.6	13.7	6.3
2	5.2	4.5	7.3	4	4.5	3	7.5	12	6.3
3	5.3	4.5	8.2	6.5	5.5	6.5	7.9	11.4	3.4
4	7.5	4.5	11	3.3	1.9	3.5	8.3	9.1	3.5
5	5.5	4.6	6.4	6.4	4.3	10	11	13.1	9
6	9.4	7.9	10.5	6	4.3	10.3	5.4	6.4	4
7	10.4	5.8	12.3	9.3	8.5	12	5.5	9.5	4
8	7.8	6.6	10.5	8.4	4.9	9.6	8.4	12.3	5
9	8.2	4.6	11	8	7.5	8	7	10.8	4
10	8	4.9	9.6	6.3	6.7	4.8	6.6	11	5
11	9.9	8	11.7	11	8.5	13.7	9	10	4.9
12	8.7	5.7	10.5	10	7.4	7.4	6.4	10	5.4
13	12.8	9.5	10.8	9	8.9	10	7.2	10.5	4
14	7.8	4.7	9.9	7.5	7.4	6.4	6.4	7.7	4.5
15	8.9	4.8	11	7.9	6.6	7.7	7.4	9.7	6.2
16	12.7	9	15.7	7.7	6.9	7.8	7	12	4.9
17	9.7	6	13.2	10.6	10.5	11.2	5	9	3.9
18	10.3	5	14.9	7.9	6.5	8.3	9.4	13.4	7.2
19	9.4	6.6	14	9.6	7.6	10	7	9.6	4
20	9.3	5.6	11.4	8	7.7	7	8	10.5	4.6
21	10.5	6.7	15.5	10.5	9	11.6	8.7	11.5	6.7
22	7.8	4.8	12	8.3	8.5	8.7	6	10.5	3

FFP- PAC- Femoral Footprint to Posterior Articular Cartilage, FFP- IAC- Femoral Footprint to Inferior Artivular Cartilage, FFP- ICR- Femoral Footprint to Intercondylar Ridge

FEMUR

Sample no.	Area			% Shallowness			% Height			DBFC	
	Whole	AM	PL	Whole	AM	PL	Whole	AM	PL	AM	PL
1	122.6017	54.8825	67.5323	37.6	30.2	44.3	48.5	62.5	31.5	6.76	7.4
2	104.0822	44.0569	61.5684	34	25.6	40	68	80.7	55.9	5.7	8
3	106.4698	48.7094	56.3041	37.5	32	42.9	63.8	82.5	52.9	6.4	7.1
4	118.0276	52.2002	68.2005	32.8	24.4	38.8	62.8	78.2	48.9	6.9	8
5	112.1858	47.8117	60.4072	37.7	31.9	43.6	61.9	76.6	46.5	5.8	7.4
6	100.9495	46.7844	54.6001	32.5	31.1	32.7	63.9	70.8	50.6	6.4	7
7	161.5125	78.9612	82.6651	42.6	37.7	49.3	60.3	76.3	47.8	8.5	9.2
8	135.4461	62.3402	74.4981	42.1	31.2	50.3	60	76	48.8	7	8.2
9	128.3956	53.7957	72.528	33.4	23.7	40.5	68.9	79.5	55.8	6.8	8.6
10	109.9713	52.2018	57.7387	27.2	19.3	37.7	60.4	73.7	49	7.3	7.2
11	127.2827	68.7544	72.2869	30.2	21.4	38.2	66.9	77.4	50.5	7.7	8.4
12	120.6737	61.8586	58.5955	32.5	23.7	39.2	63.6	74.8	48.6	7.8	7.2
13	135.8537	67.7145	67.0419	38.6	31.3	46.2	62.2	67.2	49	7.8	7.4
14	105.9997	64.4662	44.7949	31.9	27.6	36.8	67.1	78.9	47.5	7.4	5.8
15	137.0358	73.4956	63.399	36.2	28.6	45.5	56.2	66.3	53.1	8.4	7.4
16	172.5138	77.1933	95.2819	39	27.6	47.9	59.6	62.4	53.8	8.1	9.2
17	171.0719	94.5998	74.3969	29.6	23	40.5	70.1	80.9	50.9	9.1	7.6
18	164.7078	73.4888	94.4445	27.6	19.6	36.1	59.1	71.8	41.9	8.3	9.6
19	151.4432	67.142	76.802	40.9	31.4	50.6	66.3	71.4	55.2	7.4	8.6
20	119.1818	63.5616	55.407	30	22	37.7	65.9	76.7	54.8	8.1	7.5
21	189.5619	85.5747	98.0917	30.8	23.1	36.7	65.5	80.5	51.9	8.2	9.8
22	114.048	55.2394	57.5147	25.3	19.9	35.3	64	76	56.8	7	7.5

DBFC- Diameter of the best- fit circle