Original Communication

ANATOMICAL STUDY OF THE MORPHOMETRY OF THE ANTERIOR CRUCIATE LIGAMENT ATTACHMENT SITES

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RESUMEN

La incidencia de la rotura del ligamento cruzado anterior (LCA) y su consiguiente reconstrucción está en aumento. Para contribuir a la actualización de la reconstrucción anatómica del ligamento cruzado anterior, este estudio proporciona información sobre la posición y la variabilidad de los sitios de fijación en la tibia, las dimensiones de las inserciones femorales, así como las relaciones de estas mediciones en hombres y mujeres y en las rodillas derecha e izquierda. Se disecaron treinta y un (15 rodillas de cadáver derecha, 16 izquierda, de 9 mujeres y 7 hombres, con una edad media de 77 años). Se tomaron diversas dimensiones de la huella del LCA. La longitud media y la anchura de la huella del haz tibial anteromedial (AM) eran 8,9 mm y 9,8 mm mientras que la del haz posterolateral (PL) eran 9,3 mm y 8 mm respectivamente. La longitud media y la anchura de la AM tibial y paquetes PL en los varones eran 8,5 y 9,8 mm, y 9,1 y 8,3 mm, mientras que los valores correspondientes en las mujeres eran 9,2 y 9,7 mm, y 9,4 y 7,8 mm, respectivamente. Los varones tenían huellas femorales (P=0,045 para AM, P=0,043 para PL) y la meseta tibial (P<0,001) más grandes. No se observó ninguna diferencia significativa entre la rodilla derecha e izquierda. Las posiciones anatómicas medias de los haces de AM y PL fueron 46% y 50% del diámetro mediolateral de la meseta tibial. La longitud media y la anchura de los sitios de inserción femoral del LCA fueron 8,3 y 7,7 mm para el paquete de AM y 7,8 y 6,9 mm para el paquete PL respectivamente. Los parámetros más pequeños de fijación del LCA en las mujeres podría ser un factor que contribuye a la mayor incidencia de rotura del LCA en mujeres atletas.

***Palabras clave**: Ruptura del ligamento cruzado anterior; reconstrucción; fascículo antero-medial; fascículo posterolateral*

ABSTRACT

Incidence of anterior cruciate ligament (ACL) rupture and its consequent reconstruction is on the rise. In contributing to the achievement of anatomic reconstruction this study seek to provide information regarding the position and variability of the tibial attachment sites, dimensions of femoral insertions and compare these measurements in males and females, and in right and left knees. Thirty one cadaveric knees (15 right and 16 left from 9 females and 7 males, mean age 77 years) were dissected. Various ACL footprint dimensions were taken. The mean length and width of the tibial anteromedial (AM) bundle footprint were 8.9 and 9.8 mm while that of the posterolateral (PL) bundle were 9.3 and 8.0 mm respectively. The mean length and width of the tibial AM and PL bundles in males were 8.5 and 9.8 mm, and 9.1 and 8.3 mm while corresponding values in females were and 9.2 and 9.7 mm, and 9.4 and 7.8 mm respectively. Males had larger femoral footprints (P=0.020) and tibial plateau (P<0.001). No significant difference between the right and left knees were observed. The mean anatomical positions of the AM and PL bundles were 46.0% and 50.0% of the mediolateral diameter of the tibial plateau. The mean length and width of the ACL femoral insertion sites were 8.3 and 7.7 mm for the AM bundle and 7.8 and 6.9 mm for the PL bundle respectively. The smaller ACL attachment parameters in females could be a contributing factor to the higher incidence of ACL rupture in female athletes.

***Keywords**: Anatomic anterior cruciate ligament rupture; reconstruction; anteromedial bundle; postero-lateral bundle.*

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INTRODUCTION

In recent years there has been a worldwide increase in participation in sporting activities which in turn has led to an increase in the incidence of anterior cruciate ligament (ACL) injury (Unwin, 2010). As a result ACL reconstruction is one of the most common surgical procedures performed by orthopaedic surgeons (Fu et al, 2008): in the United States of America (USA) alone it is estimated that over 200,000 ACL reconstructions are performed each year (Kim et al, 2011). This is expected to increase given the level of participation in organised competitive sport at younger ages, particularly in females who have a higher risk of developing ACL injury (Arendt and Dick, 1995, Unwin, 2010). The trend is towards reconstruction techniques that more closely restore native ACL anatomy (Takahashi et al, 2006). The ACL comprises two bundles, anteromedial (AM) and posterolateral (PL), named according to their insertion on the tibia (Fu et al, 2008). In anatomic ACL reconstruction the graft is placed in the anatomic position, with tunnels drilled directly through the original attachment site, using either the single or double bundle technique (van Eck et al, 2010).

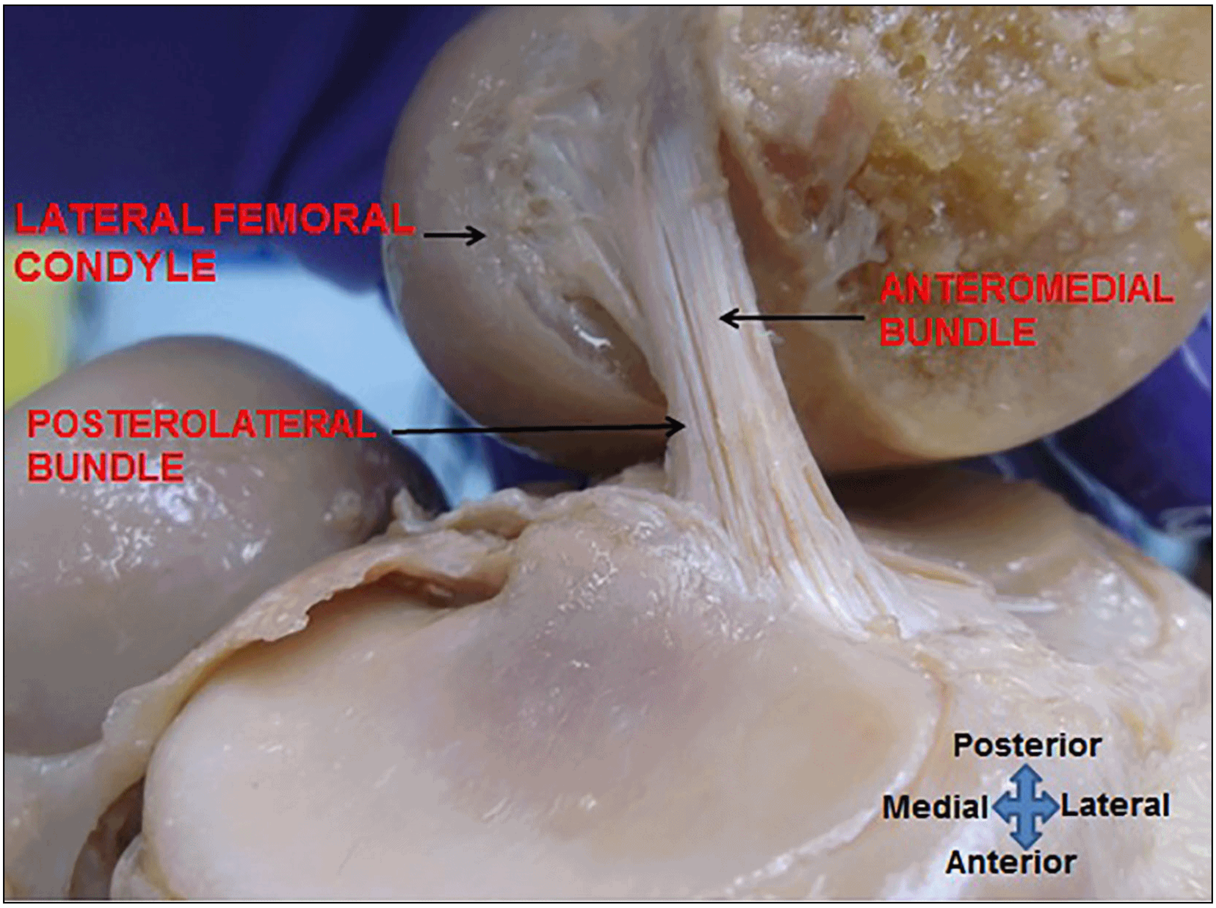

Figure 1: Bundles of the anterior cruciate ligament.

The traditional technique for ACL rupture is single bundle (SB) reconstruction, focusing on recreating the ACL as a single ligament; however this has often resulted in non-anatomic tunnel placement (Hofbauer et al, 2013). However, SB ACL reconstruction has yielded good/excellent results in only 60% of patients, with less than 50% returning to sport at their pre-injury level. Evidence also suggests that it does not protect the knee from degenerative changes, such as osteoarthritis, associated with the initial injury (Lohmander et al, 2004). There is therefore room for improvement in ACL reconstruction (Martins et al, 2012). However it is interesting to note that no advantage of the double bundle reconstruction over the single bundle reconstruction have been proven clinically (Sasaki et al, 2016) especially when an anatomic reconstruction is performed (van Eck et al, 2010). The tibial insertion size, viewed arthroscopically, plays a role in determining the technique to be selected (Kopf et al, 2011) as a tibial attachment size of less than 14 mm is too small to accommodate a double bundle reconstruction (Pombo et at, 2008). Though ACL morphometric characteristics have been extensively studied (Takahashi et al, 2006, Edwards et al, 2008, Siebold et al, 2008), however a search on Scopus revealed that there is little information on the gender difference. Relating such findings to gender could determine whether anthropometric differences in male and female ACL attachment sites play a role in the higher incidence of ACL rupture in sports women. The goal of this study is to provide information regarding the position and variability of the tibial attachment sites, dimensions of femoral insertions as well as investigate the relationships of these measurements in males and females and in right and left knees. Such information could be useful in achieving anatomical ACL reconstruction and thus individualise the procedure. Relating these findings to gender would also aid surgeons in making important decisions since ACL rupture affects both sexes.

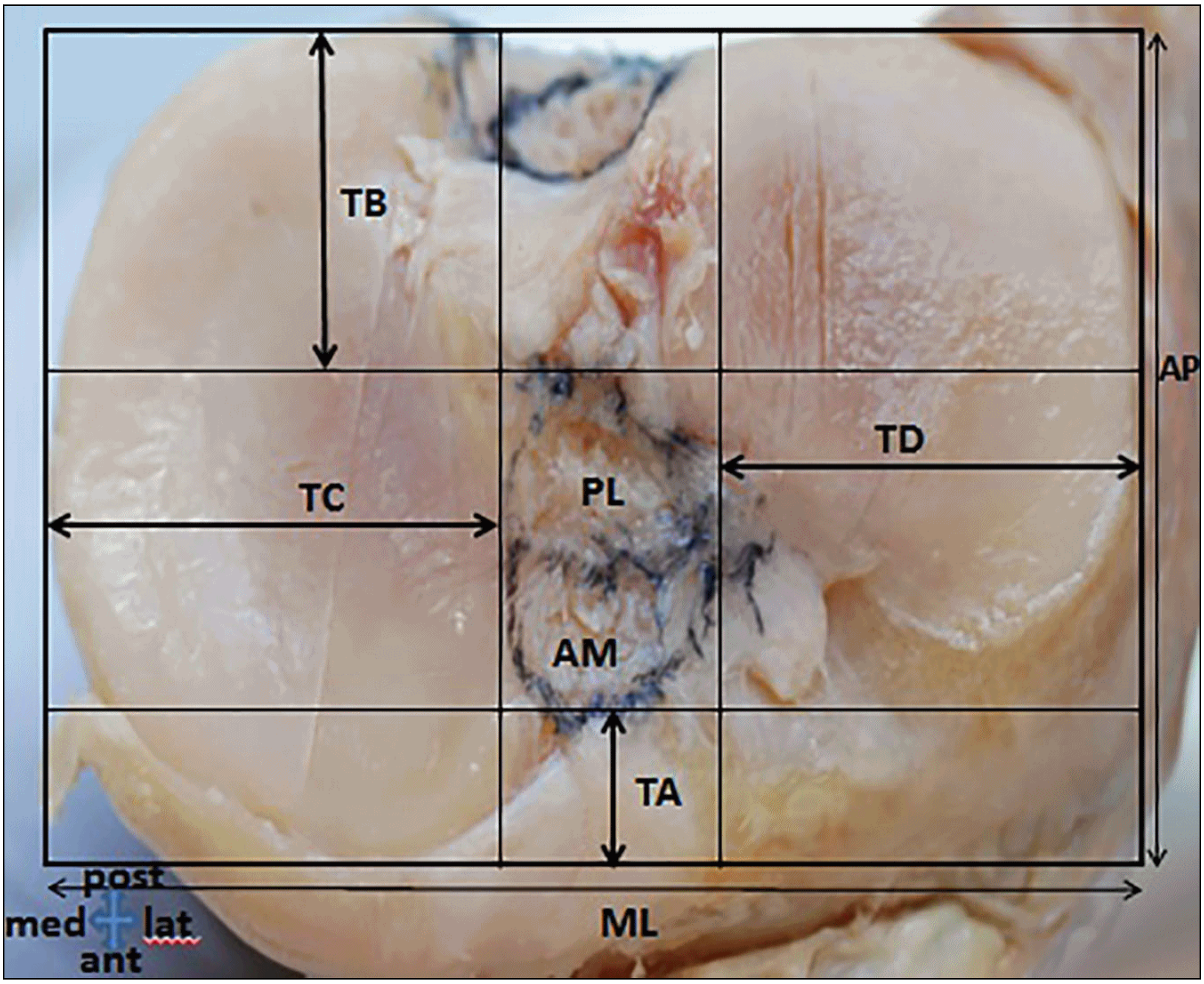

Figure 2: The tibial plateau illustrating the measurements taken in relation to the anterior cruciate ligament footprint (outlined with black ink). AP, anteroposterior diameter; ML, mediolateral diameter; TA, distance between the anterior margins of anterior cruciate ligament tibial attachment and tibial plateau; TB, distance between posterior margins of anterior cruciate ligament tibial attachment and tibial plateau; TC, distance between medial margins of anterior cruciate ligament tibial attachment and tibial plateau; TD, distance between lateral margins of anterior cruciate ligament tibial attachment and tibial plateau.

MATERIALS AND METHODS

Thirty one knees (15 right and 16 left from 9 female and 7 male cadavers) with average age of 77 years (range, 35-98 years) from 16 cadavers in the Centre for Anatomy and Human Identification, University of Dundee, were examined. All the knees were of British nationals. No cadaver presented with any sign of injury or abnormality in the knee joint: knees with severe osteoarthritic changes were excluded. All the donors and their families had agreed to their use in medical and scientific research, with all donations following the guidelines in the Human Tissues Act (Scotland) 2006.
The knee was cleared of all surrounding tissues except the ACL and posterior cruciate ligament (PCL). The intercondylar portion of the femur was sectioned between the insertions of the ACL and PCL taking care to preserve the attachment sites: the ACL attachment sites were thus exposed. The bundles of the ligament were identified (Fig. 1) and their attachment sites outlined with an ink marker after which the bundles were sectioned from the bone. The perimeter of both the tibial and femoral attachment sites were measured using a digital Vernier caliper (LUPO: accuracy 0.02 mm) with measurements taken to 0.1mm. The length and width of the attachment sites were determined. Three observers took measur-ements of each parameter and the average calculated. The anteroposterior diameter of the tibial footprint of the ACL was classified as length and the mediolateral diameter as width while the proximodistal diameter of the femoral footprint was taken as length and the anteroposterior diameter as width.
Anatomical measurements in respect of the tibial insertion are shown in Figure 2. The mediolateral diameter (ML) was the widest distance between the medial and lateral margins of the tibial plateau while the anteroposterior diameter (AP) was the perpendicular distance between the anterior and posterior margins of the articular surface of the tibial plateau. The distance (TA) between the anterior margin of the articular surface and the anterior margin of the ACL was measured. Similarly, TB was measured between the posterior margins of the ligament and articular surface. The anteroposterior position of the bundles was the percentage of the location of insertion centre calculated from the anterior margin of the articular surface in the sagittal plane. In view of the manual method of measurement, the centre point of the footprint in a particular plane was defined as half the diameter in that particular plane. Thus using simple arithmetic and as applied by Takahashi et al (2006) the anteroposterior position of the AM bundle was calculated as TA + half-length of AM/AP x 100. While that of the PL bundle was calculated as (TB + half-length of PL)-AP/AP x 100.
Similarly, the distances TC and TD between the medial and lateral margins of the ACL tibial attachment and the tibial plateau were measured. The mediolateral position of the AM bundle was calculated as TC + half-width of AM/ML x 100.

	Tibial insertion: AM bundles Length/width (mm)	Tibial insertion: PL bundles Length/width (mm)	Tibial insertion: ACL site Length/width (mm)	Femoral insertion: AM bundles Length/width (mm)	Femoral insertion: PL bundles Length/width (mm)	Femoral insertion: ACL site Length/width (mm)
Mean	8.9/9.8	9.3/8.0	14.2/11.5	8.3/7.7	7.8/6.9	14.4/9.0
SD	2.1/1.6	2.0/1.5	2.4/0.7	1.5/1.3	2.0/1.7	2.2/1.1
Range	3.4-13.7/ 6.3-12.8	6.6-15.1/ 5.3-10.8	11.1-28.8/ 8.8-12.8	6.5-12.4/ 5.8-10.9	4.7-11.7/ 4.7-12.0	11.0-20.3/ 6.8-12.0
Right knee	8.6/10.1	9.7/7.7	14.5/11.6	8.3/7.7	7.4/7.1	14.1/8.9
Left knee	9.2/9.4	8.9/8.3	14.0/11.3	8.3/7.7	8.1/6.7	14.8/9.0
Male	8.5/9.8	9.1/8.3	13.9/11.4	8.9/8.2	8.7/7.2	15.5/9.4
Female	9.2/9.7	9.4/7.8	14.5/11.5	7.8/7.4	7.2/6.7	13.6/8.7

Table 1: Sizes of the tibial and femoral anterior cruciate ligament (ACL) attachment sites. AM, anteromedial bundle; PL, posterolateral bundle; SD, standard deviation.

Data are presented as means ± standard deviations. To test for differences between gender and between right and left sides, an analysis of variance (ANOVA) was conducted. With the P value set at <0.05 = significant (*), <0.01 = highly significant (**), <0.001 = very highly significant (***), >0.05 = no significance.
To evaluate the relationship between the various ACL dimensions Pearson correlation coefficients (r) and the coefficient of determination (R^2) were calculated. SPSS software was used for the statistical analysis (IBM SPSS statistics 19). The data were checked to be normally distributed and of equal variance before undertaking the ANOVA and Pearson's tests.

RESULTS

Parameters of ACL insertions
The width and length of the ACL tibial and femoral attachment sites and its individual bundles are presented in Table 1.
Parameters of tibial attachment site
The distance between anterior edge of articular surface of the tibial plateau and anterior edge of ACL attachment was 11.7 mm (± 2.8 mm). The mediolateral and anteroposterior positions of the centre point of the ACL bundles are presented in Table 2.
Significant correlations between some variables of the ACL tibial attachment site were observed: (i) ACL attachment site length was correlated with AM length (r=0.646, P=0.000) and PL length (r=0.686, P=0.000); (ii) AM width (r=0.509, P=0.003) was correlated with total width; (iii) AM mediolateral position was correlated with AM length (r=-0.420, P=0.019) and the PL width (r=0.616, P=0.000); and (iv) anteroposterior diameter of tibial plateau (r=0.855, P=0.000) was correlated with its mediolateral diameter.
Femoral attachment
Significant correlations were observed with respect to the femoral attachment site: (i) total length was correlated with AM length (r=0.634, P=0.001) and PL length (r=0.841, P=0.001); (ii) overall width of the attachment site was correlated with AM width (r=0.602, P=0.001) and PL width (r=0.710, P=0.001). The PL bundle attachment therefore appears to influence both the length and width of the ligament attachment site.

	Mediolateral diameter of Tibial Plateau (mm)	**Anteroposterior diameter of Tibial Plateau (mm)**	**Anterior margin of ACL to AMAP (mm)**	**Mediolateral Position (%)**		**Anteroposterior position (%)**	
				AM	**PL**	**AM**	**PL**
Mean	74.9	50.8	11.7	46	50	32	51
SD	5.2	3.7	2.8	0.05	0.02	0.05	0.08
Range	67.1-82.1	44.6-57.3	8.8-15.1	38-53	46-54	19-39	33-72
Right knee	74.7	50.5	11.3	45	49	31	51
Left knee	75.0	51.2	12.1	46	50	33	51
Male	79.2	54.0	12.5	47	50	31	49
Female	71.8	48.6	11.2	45	49	32	53

Table 2: Positions of the tibial footprints of the anterior cruciate ligament (ACL) with respect to the dimensions of the tibial plateau. AM, anteromedial bundle; PL, posterolateral bundle; AMAP, anterior margin of articular plane; SD, standard deviation.

DISCUSSION

Morphometrically this study has determined the anatomical relationship of the ACL and its tibial attachment as well as the dimensions of the ligament's femoral and tibial attachment sites. These data will aid the surgeon in making critical decisions concerning graft size and type, as well as the type of procedure to use to achieve anatomic reconstruction of the ACL. This study

also compared these results between the males and females as well as between right and left knees. While there was no significant difference in the results of the right and left knees, males were found to have larger femoral footprints and tibial plateau.
Several studies (Arnoczky, 1983; Odensten and Gillquist, 1985; Colombet et al, 2006; Takahashi et al, 2006; Kopf et al, 2011) have reported the ACL to consist of two bundles. This study corroborates such findings reporting the dimensions of the tibial and femoral insertions of the bundles as well as that of the ACL as a whole (Table 1). On the tibia, the lengths of the AM and PL bundles were 8.9±2.1 mm and 9.3 ± 2.0 mm while the widths were 9.8±1.1 mm and 8.0±1.5 mm respectively. These are similar to Kopf et al (2011) who reported 9.1±1.2 mm and 7.4±1.0 mm for the length and 9.2±1.1 mm and 7.0±1.0 mm for the width respectively. A comparison of the present results with those of other authors is presented in Table 3. The different methods of measurement employed by authors are probably responsible for the differences noted: Ferretti et al (2007) used a laser scanner to obtain three-dimensional measurements, Kopf et al (2011) carried out the measurement arthroscopically, while Lee et al (2015) used digital photography.

Study	**N**	**Length of footprint (mm)**			**Width of footprint (mm)**		
		AM	**PL**	**Total ACL**	**AM**	**PL**	**Total ACL**
Tibial attachment							
Siebold et al (2008b)	46	12	10	14	5	4	10
Maestro et al (2009)	50	-	-	15.8	-		11.6
Kopf et al (2011)	137	9.1	7.4	17	9.2	7	-
Ferretti et al (2012)	8	9.8	8.7	18.1	11.1	7.9	10.7
Pujol et al (2013)	22	-	-	13.4	-	-	11.1
Lee et al (2015)	15	14.6	14.9	-	6.7	6.2	-
This study	**31**	**8.9**	**9.3**	**14.2**	**9.8**	**8**	**11.5**
Femoral attachment							
Takahashi et al (2006)	32	11.3	11	-	7.5	7.6	-
Ferretti et al (2007)	16	9.8	7.3	17.2	-	-	9.9
Edwards et al (2008)	22	7.6	6.2	14	7	5.5	7
Siebold et al (2008)	50	7	7	15	7	7	8
Kopf et al (2011)	137	9.2	7.1	16.5	8.9	6.9	-
Pujol et al (2013)	22	-	-	13.1	-	-	9.1
This study	**31**	**8.3**	**7.8**	**14.4**	**7.7**	**6.9**	**9**

Table 3: Comparison between the dimensions of the tibial and femoral anterior cruciate ligament (ACL) attachment sites reported in the literature and the current study. N, number of specimen

Regarding the location of the ACL on the tibial plateau the present study found the distance from the anterior edge of the articular surface to the anterior border of the ACL attachment to be 11.7±2.8 mm. This was similar to Compean-Martinez et al, (2013) who reported this distance to be 11.00±2.20 mm. However, Zantop et al (2006) observed it to be 15 mm: this difference was probably due to the different measurement method employed. Most previous studies on the tibial ACL insertion have used the position of the central point of the insertion as a reference for the location of the attachment site. The present study has in addition, provided the distance between the anterior edges of the ACL and the tibial articular surface. This will further aid surgeons in arthroscopic repair of the ACL. In computing the position of the centre points of the tibial AM and PL bundle attachment sites the distances from the medial, lateral, anterior and posterior margins of the tibial articular surface to the corresponding edges of the ACL tibial attachment sites were taken into consideration. The position of the central points of the bundles' tibial attachment therefore gives a reliable reference for their location in the anatomical reconstruction of the ACL. In the present study, the mediolateral position of the AM and PL bundles were 46% and 50% while antero-posterior positions were 32% and 51% respectively. These are similar to Tsukada et al (2008) who reported the mediolateral positions to be 46.5% and 51.2% and the anteroposterior positions to be 37.6% and 50.1% respectively. A comparison of the positions previously reported is presented in Table 4.

Study	N	Anteroposterior position (%)			Mediolateral position (%)		
		AM	PL	Mean	AM	PL	Mean
Takahashi et al (2006)	31	28.6	32.1	30.4	44.2	52.4	48.3
Colombet et al (2006)	7	36	52	44	-	-	-
Tsukada et al (2008)	36	37.6	50.1	43.9	46.5	51.2	48.9
Zantop et al (2008)	20	30	44	37	-	-	-
Forsythe et al (2010)	8	25	46.4	35.7	50.5	52.4	51.5
Pietrini et al (2011)	12	37.7	51.8	44.8	48	51.2	49.6
Abreu-e-Silva et al (2013)	8	-	-	40.5	-	-	50.2
The present study	**31**	**32**	**51**	**41.5**	**46**	**50**	**48**

Table 4: Comparison between the anatomical positions of the tibial anterior cruciate ligament (ACL) attachment site reported in the literature and this study. N, number of specimen

There was a very strong positive correlation between the mediolateral and anteroposterior diameters of the tibial plateau in 73.1% of specimens. This relationship most probably accounted for there being no significant difference in the position of the footprints on the tibial plateau between genders (Table 2), even though there was a significant difference (P<0.001) in the mediolateral and anteroposterior diameters of the tibial plateau between male and female knees, the males having larger diameters. Likewise ANOVA of the femoral dimensions showed significant differences between genders for the lengths of the AM (P=0.045) and PL (P=0.043) attachments, with both being longer in males. This probably contributed to the overall length of the femoral ACL attachment being significantly (P=0.020) greater in males. Morphologically the size of the attachment site can be considered to be a reflection of the size of the ligament. Females can therefore be said to have smaller ACLs compared to males. This may be a contributory factor to the higher incidence of ACL rupture in females. Though adjustments for body weight and fat were not done, this finding corroborates those of Anderson et al (2001).

The Blumensaat line, which is the roof of the intercondylar notch when viewed on conventional lateral knee radiographs, is used as a reference point for the location of the femoral ACL attachment. The centre of this attachment is located 25 to 30% of the posteroanterior dimension of the Blumensaat line (Siebold et al 2008). Furthermore, Piefer et al (2012) showed that the centre of the ACL femoral attachment is 43% of the proximodistal length of the lateral femoral intercondylar wall and 'r + 2.5' mm anterior to the posterior articular margin, where r is the ACL femoral socket radius. The femoral intercondylar region housing the femoral attachment is irregular and complex, and as such, accurate measurements with regards to the location of the footprint require the use of digital software. The present study was constrained in this regard: however, this is not the case with the location of the tibial footprint that was determined manually.

The present study has its limitations. Firstly, the average age of the cadavers was much higher than the population that undergoes ACL reconstruction: it is possible that this age difference may influence the anatomical characteristics of the ACL. Secondly, a limited number of specimens were available for study: a larger number may have demonstrated wider anatomic variation: nevertheless, the number used compares favorably with many previous studies. Furthermore, a measuring apparatus that could take into account the three-dimensional nature of the ACL and its attachment sites would have been ideal. The manual method using a digital Vernier caliper relied on human judgement that may have introduced some error.

Notwithstanding these limitations, the present study provides reliable numerical measurement of the ACL footprints, which should contribute to a better understanding of ACL anatomy and potentially aid in making appropriate decisions on the type of graft, the position of tunnels and technique (i.e. single or double bundle) used in ACL reconstruction. Further studies are recommended to verify whether the smaller size of the ligament in the female is a contributory factor to the higher incidedent of its rupture in female athletes.

Conflict of Interest
None.

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None to be decleared.

Contributions
The authors hereby confirm that this manuscript is original and have not been published or awaiting publication in any journal. The contributions of the authors are as described below:

Iyaji PI: Conception and design of the study, acquisition of data, analysis and interpretation of data, drafting the article, final approval of the version to be submitted. Alashkham A: Conception and design of study, acquisition of data, drafting the article, final approval of the version to be submitted. Alraddadi A: Analysis and interpretation of data, drafting the article, final approval of the version to be submitted. Soames R: Conception and design of the study, acquisition of data, analysis and interpretation of data, drafting the article, final approval of the version to be submitted.

Informed Consent and Ethical Approval
All the donors and their families had agreed to their use in medical and scientific research, with all donations following the guidelines in the Human Tissues Act (Scotland) 2006. Given that no data allowing the identification of the individuals were presented, the publication of this study poses no ethical problem.

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