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ORIGINAL ARTICLE • KNEE - ANATOMY

The correlation between the femoral anterior cruciate ligament footprint area and the morphology of the distal femur: three-dimensional CT evaluation in cadaveric knees

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Abstract

Backgrounds "Anatomical" anterior cruciate ligament (ACL) reconstruction is defined as the functional restoration of the ACL to its native dimensions. It is essential to obtain more accurate predictors of ACL size before surgery. The purpose of this study was to investigate the correlation between the native femoral ACL footprint size and the morphology of the distal femur using three-dimensional CT (3D-CT).

Methods Thirty non-paired Japanese human cadaver knees were used. All soft tissues around the knee were resected except the ACL. For the evaluation of femoral condyle morphology, trans-epicondylar length (TEL), notch outlet length, axial notch area, and notch width index were measured using 3D-CT. The ACL was cut in the middle, and the femoral bone was cut at the most proximal point of the femoral notch. The ACL was carefully dissected, and the boundaries of the ACL insertion site were outlined on the femoral side. An accurate lateral view of the femoral condyle was photographed with a digital camera. The size of the femoral ACL footprint, length of Blumensaat's line, and the height and area of the lateral wall of the femoral intercondylar notch were measured with ImageJ software.

Results Notch height, lateral notch area, and TEL were significantly correlated with the femoral ACL footprint area. Both axial notch area and notch outlet length were significantly correlated with the femoral mid-substance insertion area.

Conclusion Morphological evaluation using 3D-CT preoperatively may be useful in predicting the femoral ACL footprint size.

Keywords Anterior cruciate ligament · Anteromedial bundle · Posterolateral bundle · Fan-like extension fibers · Mid-substance

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Introduction

In recent decades, anatomical anterior cruciate ligament (ACL) reconstruction has become more popular, and numerous studies have reported its superior ability to restore normal knee function compared to non-anatomical reconstruction. [1–7]. With the increasing frequency of anatomical ACL reconstruction, the anatomy of the ACL is being studied in greater detail [1, 8, 9]. However, the reported anatomy of the ACL varies widely depending on the study [10–15], and the optimal placement of anatomical tunnels remains unclear.

One of the final goals of anatomical ACL reconstruction is the restoration of native anatomy [8, 16]. However, in most cases of ACL reconstruction using autograft, the reconstructed ACL size is determined by the harvested graft size, not by the size of the native ACL insertion site [2, 4, 6, 17]. If the harvested graft size is small, the resulting reconstructed ACL is also small, even when the native insertion site is comparatively large. Determining the reconstructed ACL size by the harvested graft size alone is insufficient. It is essential to obtain more accurate predictors of ACL size before surgery. If surgeons can predict the ACL size using radiographic measurements, they can easily select the optimal type of autograft and allograft before surgery. Several studies have reported that intercondylar notch width is significantly correlated with ACL size [4, 18–21]. However, no study has attempted to examine the correlation between the native femoral ACL footprint size and the size of the femoral condyle.

The purpose of this study was to investigate the correlation between the native femoral ACL footprint size and the size of the femoral condyle in cadaveric knees using three-dimensional CT (3D-CT).

The hypothesis of this study was that the native femoral ACL footprint size would be significantly correlated with the size of the femoral condyle. For clinical relevance, establishing such a correlation would allow surgeons to predict the native ACL size by measuring femoral condyle morphology.

Materials and methods

Thirty non-paired Japanese human cadaver knees were used (15 males, 15 females, median age 78.8, range 53–94). Knees with severe osteoarthritic changes were not included in this study.

Evaluation of femoral condyle morphology using 3D-CT

All soft tissues around the knee were resected except the ligaments. Knees were cut at approximately 200 mm proximal to the femur and distal tibia. CT (Alexion; Toshiba, Co, Ltd., Tokyo, Japan) scans of the knees were performed. The slice of the CT image which revealed the greatest length between the medial and lateral epicondyles of the femur (trans-epicondylar length: TEL) was used. TEL, the length of the notch outlet, and the length of the medial and lateral posterior condyle were measured. Notch width index (NWI) was calculated as the length of the notch outlet/the length of the medial and lateral posterior condyle $\times$ 100 (%). The axial notch area was evaluated using the same slice of the CT image. The notch was outlined, and the posterior border of the notch was determined as the line between the inside medial and lateral femoral condyles exhibiting a sudden change in slope [20]. All CT measurements were taken with PACs system (Fig. 1).

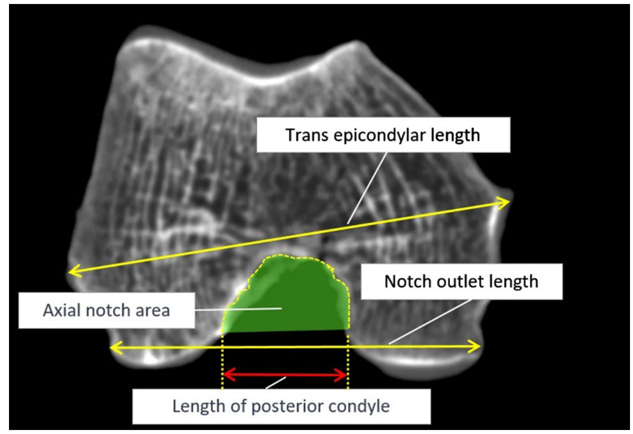

Fig. 1 CT measurement of the femoral condyle. For the evaluation of femoral condyle morphology, trans-epicondylar length (TEL), notch outlet length, axial notch area, and notch width index (NWI) were measured using 3D-CT

Evaluation of the ACL insertion site

All surrounding muscles and other soft tissues around the knee were resected before ACL dissection. All soft tissues were carefully dissected. When the surrounding synovial tissues were dissected, fibers of the ACL were revealed. After soft tissue resection, the ACL was cut in half. On the femoral side, the femur was split along the sagittal plane through the most superior point of the anterior outlet of the intercondylar notch with an oscillating saw to expose the femoral attachment of the ACL. First, the outline of the whole femoral ACL footprint was marked with colored ink, and then the mid-substance insertion site was marked in a similar fashion [22]. As reported by Mochizuki et al. [23], a fold was present between the mid-substance insertion site and the fanlike extension fiber and could be detected macroscopically. Referring to the mid-substance tissue of the ACL, the border between the mid-substance insertion area and the fanlike extension fibers was clearly distinguished [22–24]. An accurate lateral view of the femoral condyle was photographed with a digital camera (Casio, Co. Ltd., Tokyo, Japan) [22]. The images were downloaded to a personal computer, and the footprint area was calculated after adjusting the computer images to the actual knee size using ImageJ software (National Institute of Health). The accuracy of the area measurement was less than 0.1 mm^2. The following areas were calculated: the whole ACL area and the mid-substance insertion area (Fig. 2).

Cadaveric measurement of the size of the lateral femoral condyle

With the same images used in the ACL footprint evaluation, the length of Blumensaat's line and the height and area

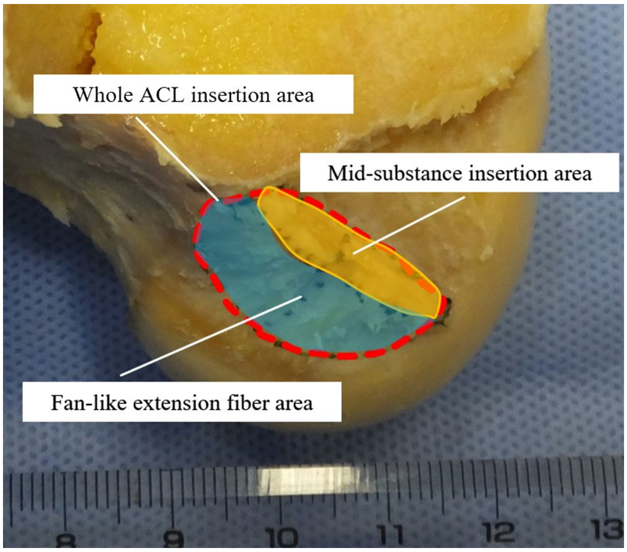

Fig. 2 Evaluation of the femoral ACL footprint. The ACL was carefully dissected, and the periphery of the ACL insertion site was outlined on the femoral side. The whole ACL footprint and the mid-substance area of the ACL footprint were evaluated

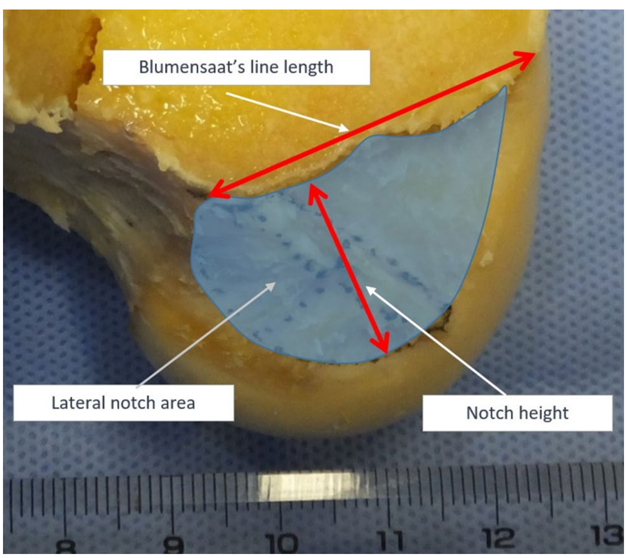

Fig. 3 Cadaveric assessment of the femoral condyle. Using the same image used in the femoral ACL footprint evaluation, the length of Blumensaat's line and the height and area of the lateral wall of the femoral intercondylar notch were measured with ImageJ software

(lateral notch area) of the lateral femoral condyle were measured with ImageJ software [25, 26] (Fig. 3).

Statistical analysis

Data are presented as mean ± standard deviations. The Pearson's product movement correlation was calculated to reveal the correlation between the whole femoral ACL insertion area, the mid-substance insertion area, and:

CT measurement

- TEL
- notch outlet length
- posterior condyle length
- NWI
- axial notch area

Cadaveric measurement

- length of Blumensaat's line
- height of the lateral wall of the femoral intercondylar notch (notch height)
- area of the lateral wall of the femoral intercondylar notch (lateral notch area)

Statistical significance was assumed when $P < 0.05$. All statistical data were calculated with SPSS 19.0 (SPSS Inc., Chicago, IL, USA). Considering the mean and standard deviations of the notch height, the calculated sample size was 27.4 (G*Power 3 software). This research has been approved by the IRB of the authors' affiliated institutions.

Results

CT measurement

The average TEL, notch outlet length, NWI, and axial notch area were 77.8 ± 6.4 mm, 20.5 ± 3.1 mm, 30.8 ± 4.1%, and 265.7 ± 73.1 mm^2, respectively.

Cadaveric measurement

The measured areas of the whole femoral ACL footprint, the mid-substance insertion site, and the fanlike extension fiber area were 125 ± 47 mm^2, 67 ± 21 mm^2, and 59 ± 31 mm^2, respectively.

The length of Blumensaat's line, notch height, and lateral notch area were 32.2 ± 3.9 mm, 15.3 ± 2.0 mm, and 393.8 ± 85.1 mm^2, respectively.

Correlation between the whole femoral ACL insertion area and the bony morphology of the femoral condyle

TEL, lateral notch area, and notch height were significantly correlated with the whole femoral ACL insertion area. The notch outlet length, NWI, notch axial area, and the length of

Blumensaat's line were not correlated with the whole femoral ACL insertion area (Table 1).

Correlation between the mid-substance insertion area and the bony morphology of the femoral condyle

The axial notch area and notch outlet length were significantly correlated with the mid-substance insertion area. TEL, NWI, lateral notch area, notch height, and the length of Blumensaat's line were not correlated with the mid-substance insertion area (Table 1).

Discussion

The most important finding of this study was that significant correlations were observed between the femoral ACL insertion area and the bony morphology of the femoral condyle. TEL, notch height, and lateral notch area showed a significant correlation with the whole ACL insertion area. Axial notch area and notch outlet length showed a significant correlation with the mid-substance insertion area. These results suggest that the size of ACL can be estimated before surgery by measuring the size of the femoral condyle using a lateral knee radiograph, CT, or magnetic resonance imaging (MRI).

In order to perform accurate anatomical ACL reconstruction, prediction of the native ACL size is essential. However, few studies have suggested that an accurate prediction of ACL size can be obtained by measuring the knee bony morphology. In countries which allow the use of allografts for ACL reconstruction, surgeons can use allografts large enough to reproduce the native ACL [26]. However, in countries which do not permit the use of allografts, surgeons must use autografts [2, 4, 6, 17]. Recently, the efficacy of the double-bundle technique [2, 6, 7, 16] and the rectangular bone–patellar tendon–bone (BPTB) technique [17] in accurately reproducing the anatomical footprint in ACL reconstruction has been investigated. Although double-bundle and rectangular BPTB techniques are suitable in terms of fitting the graft within the ACL footprint, the reconstructed ACL graft size should be as large as and as close in size to that of the native ACL. In most cases of ACL reconstruction using autografts, the reconstructed ACL size is mainly determined by the harvested graft size, not by the size of the ACL footprint. Iriuchishima et al. [26] previously reported that no correlation existed between commonly used autograft size and ACL footprint size. In the reproduction of native ACL morphology, there is a risk of failure when surgeons determine the reconstructed ACL size by the harvested graft size alone. Our study shows that a more accurate prediction of ACL footprint size can be made by measuring the size of the femoral condyle, which will assist surgeons in selecting and harvesting the most suitably sized autograft.

A significant correlation between notch width and ACL size has been reported by several authors [4, 18–21]. Stijak et al. [19] conducted a cadaveric study and found that ACL width was in positive correlation with the intercondylar notch width in male subjects. However, the same correlation did not exist in female subjects. In the

Table 1 Correlation between whole ACL footprint area, mid-substance insertion area, and CT/cadaveric measurements

(mean ± SD)	Whole ACL insertion		Mid-substance	
	P value	Pearson's coefficient correlation	*P* value	Pearson's coefficient correlation
Cadaveric measurement				
Lateral notch area (393.8 ± 85.1 mm^2)	* 0.001	0.697	0.219	0.267
Blumensaat's line length (32.2 ± 3.9 mm)	0.107	0.345	0.485	0.153
Notch height (15.3 ± 2.0 mm)	* 0.03	0.453	0.233	0.259
CT measurement				
Axial notch area (265.7 ± 73.1 mm^2)	0.112	0.341	* 0.029	0.455
NWI (30.8 ± 4.1%)	0.558	0.129	0.111	0.341
Notch outlet length (20.5 ± 3.1 mm)	0.133	0.323	* 0.03	0.452
TEL (77.8 ± 6.4 mm)	* 0.01	0.512	0.110	0.342

NWI notch width index, *TEL* trans-epicondylar length

*$P < 0.05$

cadaveric study of Muneta et al. [4], the notch width was correlated with the cross-sectional area of the ACL. In the recent work of Wu et al. [27], no significant correlation was observed between ACL footprint size and body height or gender. Such results indicate that morphological knee measurement is more accurate than body size or gender as a predictor of ACL size before surgery. As van Eck reported [28], not only the size of the intercondylar notch, but also the shape of the notch might be correlated with the size of the ACL. Iriuchishima et al. [25] reported that the size of the tibial ACL footprint has a significant correlation with the anteroposterior length of the lateral facet of the tibia plateau and the area of the tibia plateau. When the suspected ACL footprint is large, the combined use of semitendinosus and gracilis tendon for the graft is recommended to fill the ACL footprint. To ensure the true efficacy of anatomical ACL reconstruction using autograft, as van Eck et al. recommended [16], the native femoral ACL footprint size should be evaluated first, followed by careful graft selection. For clinical relevance, the results of this study indicate that femoral condyle morphology should be measured prior to graft selection in the planning stages of ACL reconstruction using autograft.

The main limitations of this study were (1) the ACL dissection was performed only by macroscopic evaluation. Although the dissection was made by experienced surgeons, this might allow for human error and bias. Although the border between the mid-substance insertion and fanlike extension fibers of the ACL could be determined clearly by macroscopic evaluation, and the significant correlation between the macroscopic border and the histological border has been previously reported [3], a more detailed histological evaluation should be attempted in future plans. (2) Only Japanese subjects were included in this study. Ethnicity might be a potential influence and should be taken into consideration in future studies. (3) The average age of the cadavers used was significantly older than the average age of patients that undergo ACL reconstruction. Even though no specimens had severe osteoarthritic changes, the ages of the specimens should be considered in such an anatomical study. (4) Our sample size was not large ($n = 30$) but was similar to previous studies [9, 22, 24]. However, due to anatomical variation and in order to accurately define the ACL anatomy, a study with a larger sample size is needed. (5) The femoral ACL footprint was evaluated using a two-dimensional technique. The ACL is attached three-dimensionally to the bone [8] and might be better evaluated three-dimensionally.

For clinical relevance, an accurate prediction of the femoral ACL footprint can be achieved by evaluating femoral condyle morphology preoperatively using 3D-CT.

Conclusion

In conclusion, notch height, sagittal notch area, and TEL were significantly correlated with the area of the whole femoral ACL footprint. Axial notch area and notch outlet length were significantly correlated with the femoral mid-substance insertion area. For clinical relevance, preoperative measurement of the bony knee morphology of the distal femur can be an effective means of predicting native ACL size, allowing surgeons to select the most suitable graft for ACL reconstruction.

Compliance with ethical standards

Conflict of interest The authors have no financial relationships to disclose.

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