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ACL footprint size is correlated with the height and area of the lateral wall of femoral intercondylar notch

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Abstract
Purpose The purpose of this study was to reveal the correlation between the size of the native anterior cruciate ligament (ACL) footprint and the size of the lateral wall of femoral intercondylar notch.
Methods Eighteen non-paired human cadaver knees were used. All soft tissues around the knee were resected except the ACL. 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 periphery of the ACL insertion site was outlined on both the femoral and tibial sides. An accurate lateral view of the femoral condyle and the tibial plateau was photographed with a digital camera, and the images were downloaded to a personal computer. The size of the femoral and tibial ACL footprints, length of Blumensaat's line, and the height and area of the lateral wall of femoral intercondylar notch were measured with Image J software (National Institution of Health).
Results The sizes of the native femoral and tibial ACL footprints were 84 ± 25.3 and 144.7 ± 35.9 mm^2, respectively. The length of Blumensaat's line and the height and area of the lateral wall of femoral intercondylar notch were 29.4 ± 2.8 mm, 17.1 ± 2.7 mm, and 392.4 ± 86 mm^2, respectively. Both the height and the area of the lateral wall of femoral intercondylar notch were significantly correlated with the size of the ACL footprint on both the femoral and tibial sides.
Conclusion For clinical relevance, the height and area of the lateral wall of femoral intercondylar notch can be a predictor of native ACL size prior to surgery. However, the length of Blumensaat's line showed no significant correlation with native ACL size.

Keywords Anterior cruciate ligament · Anatomy · Double bundle · Femoral condyle

Abbreviations
ACL Anterior cruciate ligament
AM Antero-medial bundle
PL Postero-lateral bundle

Introduction

Anatomical anterior cruciate ligament (ACL) reconstruction is becoming more popular due to numerous studies reporting its superior ability to restore normal knee function when compared to non-anatomical reconstruction [8, 13, 14, 17, 19, 20, 36–38]. With the rising frequency of anatomical ACL reconstruction [31], the anatomy of the ACL has been studied in greater detail [5, 8, 9, 15].

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However, reports vary as to the exact anatomy of the ACL [7, 16, 21, 26, 27], and the optimal placement of anatomical tunnels in anatomical ACL reconstruction remains unclear.

One of the final goals of anatomical ACL reconstruction is the restoration of native anatomy [5, 6]. 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 [14, 20, 22, 25, 37]. 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 autografts and allograft before surgery. Several studies have reported that intercondylar notch width is significantly correlated with the size of the ACL [4, 20, 29, 32, 34]. However, no study has reported the correlation between native ACL footprint size and the size of the lateral wall of femoral intercondylar notch.

The purpose of this study was to reveal the correlation between native ACL footprint size and the size of the lateral wall of femoral intercondylar notch using cadaveric knees.

The hypothesis of this study was that native ACL footprint size would be correlated with the size of the lateral wall of femoral intercondylar notch.

Materials and methods

Eighteen non-paired formalin-fixed Japanese cadaveric knees were used (7 men, 11 women; median age, 83; range, 68–97). Knees with severe osteoarthritic changes were excluded from this study.

Evaluation of ACL insertion site

All surrounding muscles, ligaments, and other soft tissues in the knee were resected before ACL dissection. Particular care was taken to ensure that the posterior structures were accurately resected. The posterior joint capsule, menisco-femoral ligaments, posterior cruciate ligament (PCL), and synovial tissues were resected carefully to simulate accurate ACL dissection. After soft tissue resection, the ACL was cut into 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. The outline of the femoral ACL footprint was marked with coloured ink. On the tibial side, posterior synovial tissue and blood vessels were carefully resected, and the outline of the footprint was also marked (Fig. 1). Antero-medial (AM) and postero-lateral (PL) bundles were not separated in this study because the purpose was to evaluate the total ACL area correctly. After marking the ACL footprint, an accurate lateral view of the femoral condyle and an accurate axial view of the tibia plateau were photographed with a Casio EXILIM S12 digital camera (Casio, Co. Ltd., Tokyo, Japan). Adjusting to the real knee size and computer image calculation, measure was also photographed within the same image. The images were downloaded to a personal computer, and the footprint area was analysed using Image J software (National Institute of Health) [23, 24]. The accuracy of the area measurement was less than 0.1 mm^2 (Fig. 1).

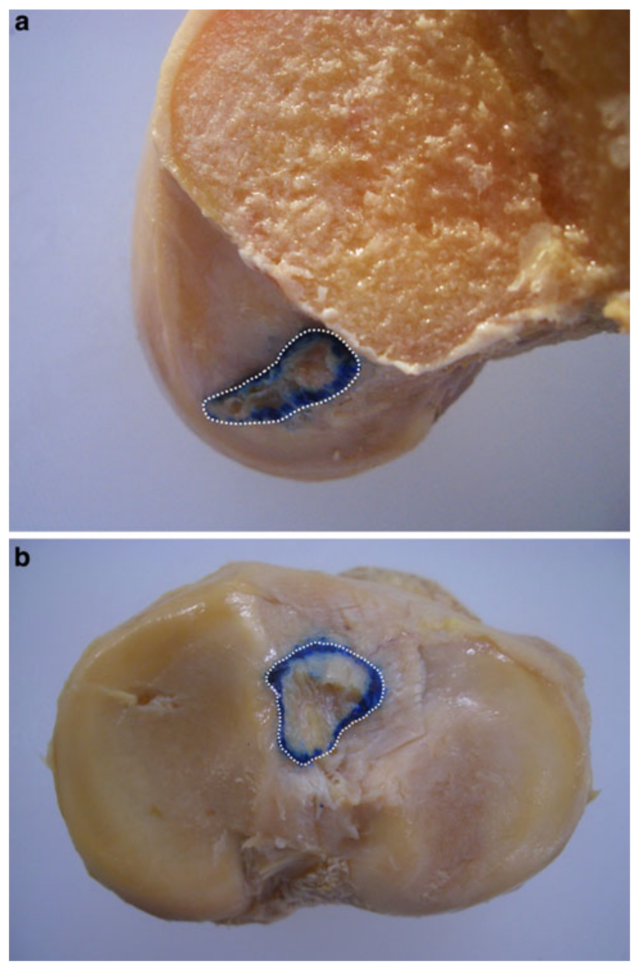

Fig. 1 Measurement of ACL footprint size. After marking an outline of the ACL footprint, each footprint was photographed with a digital camera. The pictures were downloaded to a personal computer, and the area of the footprint was analysed using Image J software (National Institute of Health)

Measurement of the size of the lateral wall of femoral intercondylar notch

With the same images used in the ACL footprint evaluation, the height, area, and length of Blumensaat's line of the lateral wall of femoral intercondylar notch were measured with Image J software (Fig. 2).

Statistical analysis

Data are presented as mean ± standard deviations. The Pearson's product movement correlation was calculated to reveal the correlation between the following:

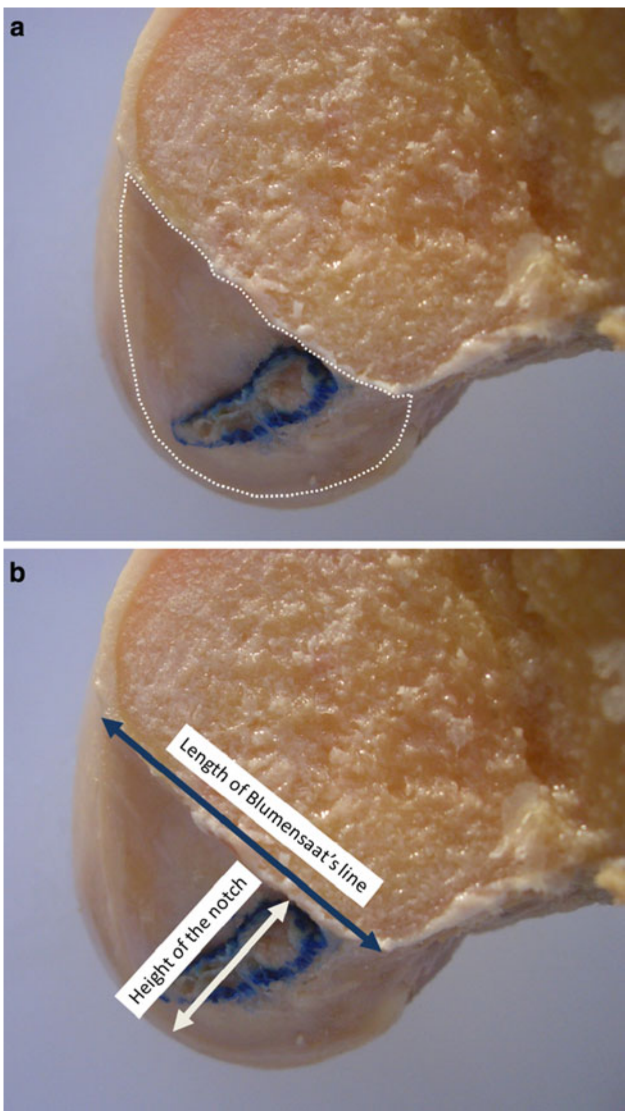

Fig. 2 Measurement of lateral wall of femoral intercondylar notch size. With the same pictures used in the ACL footprint evaluation, the area of the lateral wall of femoral intercondylar notch (**a**), the length of Blumensaat's line, and the height of the lateral wall of femoral intercondylar notch (**b**) were measured with Image J software

- Femoral footprint size and tibial footprint size
- The length of Blumensaat's line and femoral or tibial footprint size
- The height of the lateral wall of femoral intercondylar notch and femoral or tibial footprint size
- The area of the lateral wall of femoral intercondylar notch and femoral or tibial footprint size

It was assumed that there was statistical significance when $P < 0.05$. All statistical data were calculated with SPSS 19.0 (SPSS Inc., Chicago, IL, USA).

Results

ACL footprint size and area

The measured areas of the femoral and tibial ACL footprint were 84.0 ± 25.3 mm^2 and 144.7 ± 35.9 mm^2, respectively.

Lateral wall of femoral intercondylar notch height, area, and length of Blumensaat's line

The height of the lateral femoral condyle was 17.1 ± 2.7 mm. The area of the lateral femoral condyle was 392.5 ± 86.0 mm. The length of Blumensaat's line was 29.4 ± 2.8 mm^2.

Size comparison of ACL footprint and lateral femoral condyle

The size of the femoral and tibial ACL footprints was significantly correlated (Pearson's correlation coefficient = 0.681, $P = 0.002$). The height of the lateral wall of femoral intercondylar notch was significantly correlated with the size of the femoral ACL footprint (Pearson's correlation coefficient = 0.868, $P = 0.000$) and tibial ACL footprint (Pearson's correlation coefficient = 0.768, $P = 0.000$; Fig. 3). The area of the lateral wall of femoral intercondylar notch showed significant correlation with the size of the femoral ACL footprint (Pearson's correlation coefficient = 0.782, $P = 0.000$) and the tibial ACL footprint (Pearson's correlation coefficient = 0.608, $P = 0.008$; Fig. 4). The length of Blumensaat's line showed no significant correlation with the size of the ACL footprint at either the femoral or tibial side.

Discussion

The most important finding of this study was that both the height and the area of the lateral wall of femoral

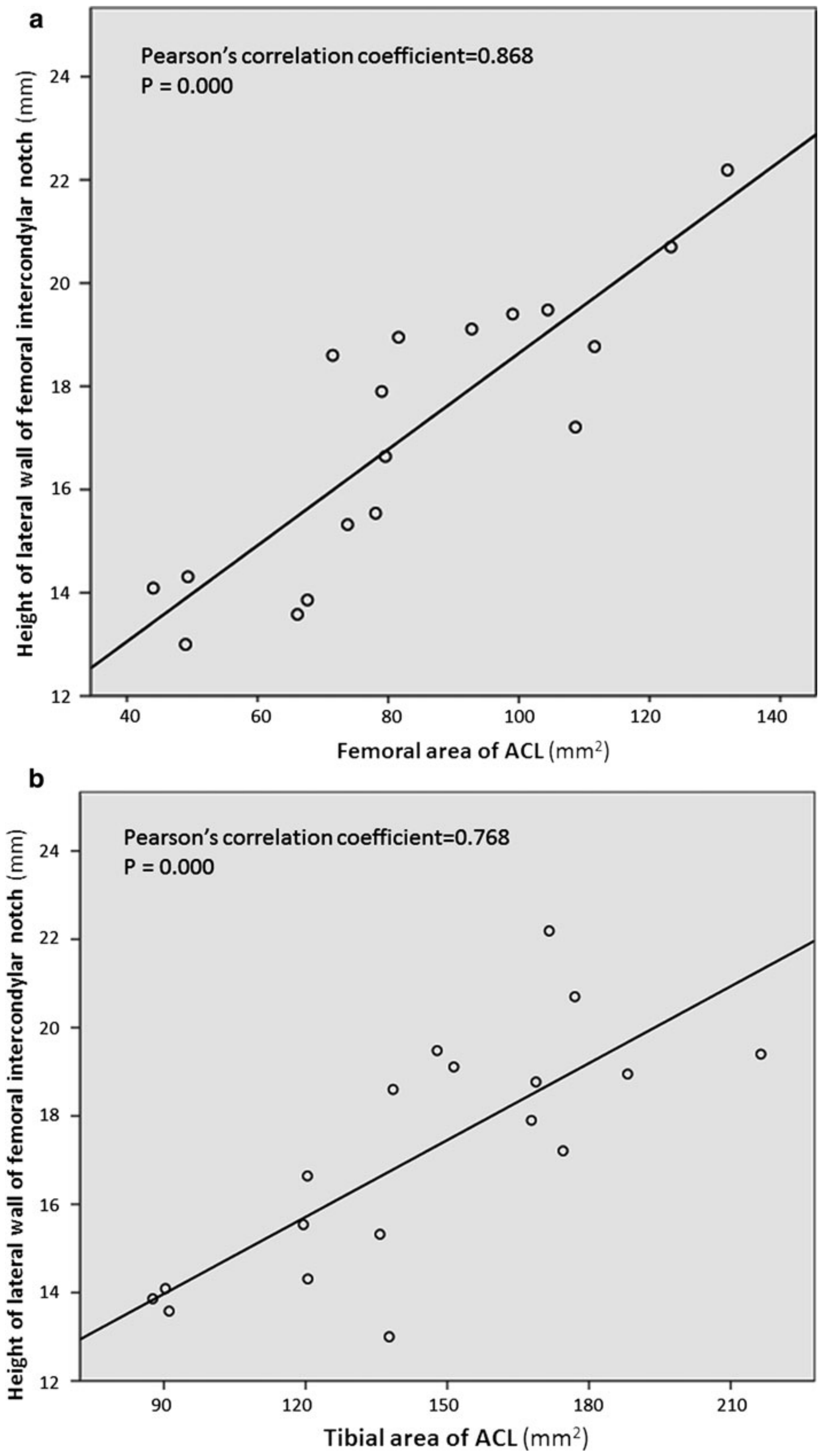

Fig. 3 Correlation analysis of lateral wall of femoral condylar notch height and ACL footprint size. The size of the femoral (**a**) and tibial (**b**) ACL footprints showed significant correlation with the height of the lateral wall of femoral intercondylar notch

intercondylar notch showed significant correlation with the size of the ACL footprint. However, the length of Blumensaat's line showed no significant correlation with the size of the ACL footprint. Although this study did not include a radiographic evaluation, the results suggest that the size of the ACL footprint can be predicted before

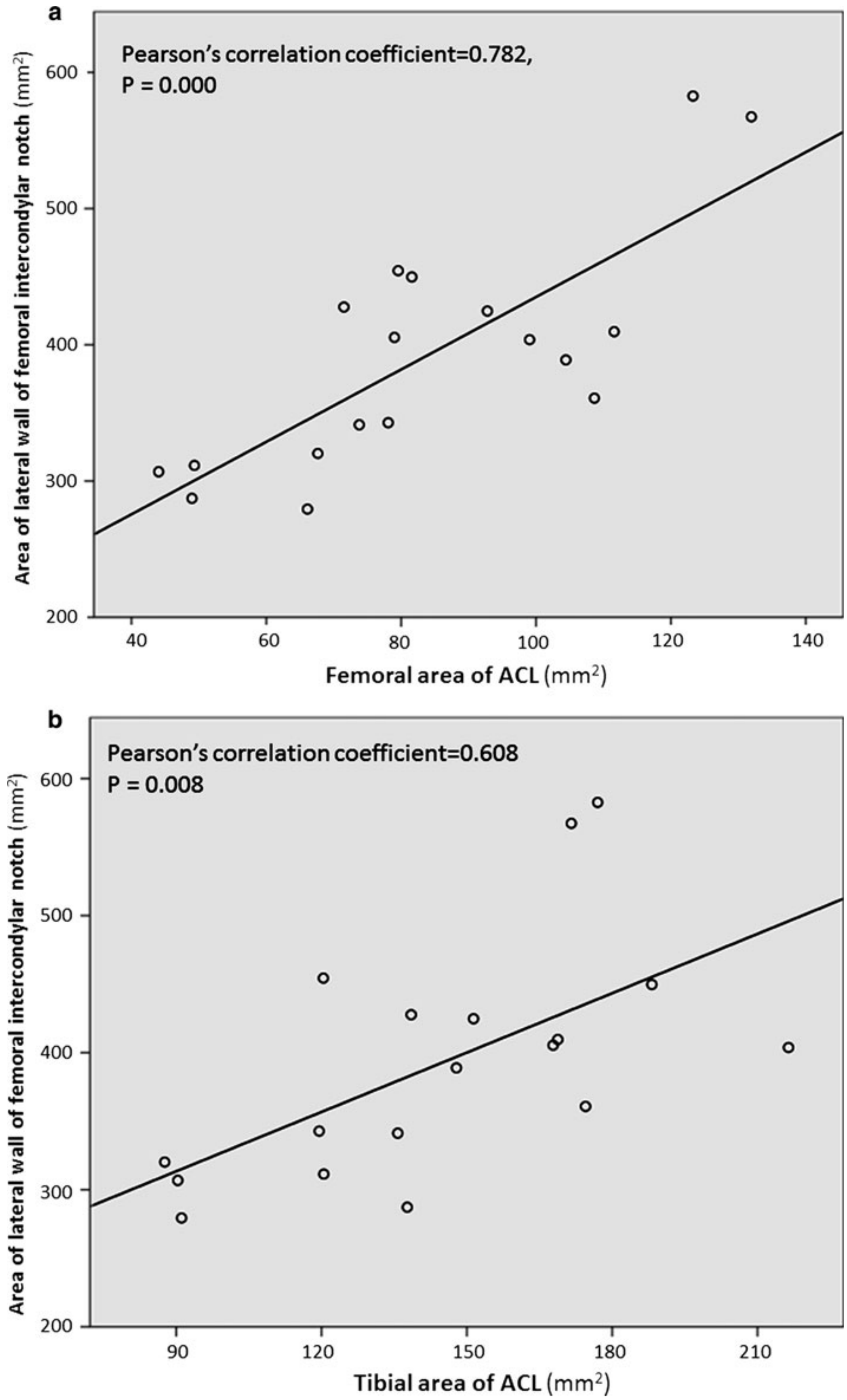

Fig. 4 Correlation analysis of lateral wall of femoral intercondylar notch area and ACL footprint size. The size of the femoral (**a**) and tibial (**b**) ACL footprints showed significant correlation with the area of the lateral wall of femoral intercondylar notch

surgery by measuring the size of the lateral wall of femoral intercondylar notch using a lateral knee radiograph, computed tomography, or magnetic resonance imaging.

In recent ACL studies, anatomical evaluation of correct tunnel placement, biomechanical testing, and graft healing have been reported [1, 2, 5, 8, 9, 13, 28, 37, 39]. However, the size of the reconstructed graft has not been well documented. As ACL reconstruction is a kind of graft transplantation, the size of the graft should be evaluated in greater detail.

In countries that allow the use of allografts for ACL reconstruction, surgeons can use allografts large enough to reproduce the native ACL [6]. However, in countries that do not permit the use of allografts, surgeons must use autografts [14, 20, 22, 25, 37]. In isometric, non-anatomical, single-bundle ACL reconstruction, large 4-strand ST-G grafts or larger BTB grafts were commonly used as autografts [22, 28]. However, it is now known that the native ACL footprint cannot be reproduced with such a large, circular tunnel [10, 38]. Recently, the efficacy of the double-bundle technique [6, 12, 13, 14, 37–39] and the rectangular BPTB technique [25] in accurately reproducing the anatomical footprint in ACL reconstruction has been investigated. Although the double-bundle and the 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. However, 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. If the surgeons can easily predict the size of the ACL footprint before surgery, they can select and harvest the most suitably sized autograft.

A significant correlation between notch width and ACL size has been reported by several authors [4, 20, 29, 32, 34]. Stijak et al. [29] 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 cadaveric study of Muneta et al. [20], the notch width was correlated with the cross-sectional area of the ACL. Davis et al. [4] also reported that the width of mid-substance ACL had a significant correlation with the notch width. However, they did not measure the correlation between the ACL footprint size and the length of Blumensaat's line or notch height, both of which can be easily measured in a lateral knee radiograph. In the recent work of Wu et al. [35], no significant correlation was observed between the ACL footprint size and body height or gender. Therefore, morphological knee measurement is more accurate than body size or gender as a predictor of ACL size before surgery. As van Eck reported [33], not only the size of the intercondylar notch but also the shape of the notch might be correlated with the size of ACL.

Normally used autografts for ACL reconstruction are semitendinosus tendon, the combined use of semitendinosus and gracilis tendon, bone-patella tendon-bone graft, and quadriceps tendon. As the results of this study show, the size of the ACL footprint has a significant correlation with the height and the area of the lateral wall of femoral intercondylar notch. The strongest correlation was observed between the height of the lateral wall of femoral intercondylar notch and the size of the femoral ACL footprint. In the planning stages of ACL reconstruction using autograft, these parameters should be measured prior to graft selection. 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.

Several studies have reported on the size of the ACL footprint [3, 5, 7, 18, 21, 26, 27, 30]. For the femoral footprint, the range in reported size was 83–196.8 mm^2. On the tibia side, the range in footprint size was 114–229 mm^2. The results of our study regarding the size of the ACL footprint were similar to those of previous reports. As previously reported [7, 26, 27] and confirmed in this study, the size of the ACL varies greatly. To ensure the true efficacy of anatomical ACL reconstruction using autograft, as Fu et al. [6] recommended, the size of the native ACL footprint should be evaluated first, followed by careful graft selection.

The main limitations of this study were the following: (1) the ACL dissection was performed only by macroscopic evaluation. Although this dissection was made by experienced surgeons, this might allow for human error and bias. (2) 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. (3) Our sample size was not large ($n = 18$) but was similar to a previous study [11]. However, due to anatomical variation and in order to accurately define the ACL anatomy, a study with a larger sample size is needed. (4) The ACL footprint was only evaluated with a 2-dimensional technique. The ACL is attached 3-dimensionally to the bone [5] and might be better evaluated with a 3D camera or computer graphics.

Conclusion

In conclusion, the height and area of the lateral wall of femoral intercondylar notch showed significant correlation with the size of the ACL footprint. However, the length of Blumensaat's line showed no significant correlation with the size of the ACL footprint. For clinical relevance, the preoperative measurement of these parameters might be an effective means of predicting the native ACL size, allowing surgeons to select the most suitable graft for ACL reconstruction.

References

1. Brophy RH, Selby RM, Altchek DW (2006) Anterior cruciate ligament revision: double-bundle augmentation of primary vertical graft. Arthroscopy 22 (6):683 e1–683 e5

2. Darcy SP, Kilger RH, Woo SL, Debski RF (2006) Estimation of ACL forces by reproducing knee kinematics between sets of knees: a novel noninvasive methodology. J Bionech 39(13): 2371–2377
3. Dargel J, Pohl P, Tzikaras P et al (2006) Morphometric side-to side differences in human cruciate ligament insertions. Surg Radiol Anat 28(4):398–402
4. Davis TJ, Shelbourne KD, Klootwyk TE (1999) Correlation of the intercondylar notch width of the femur to the width of the anterior and posterior cruciate ligaments. Knee Surg Sports Traumatol Arthrosc 7:209–214
5. Ferretti M, Ekdahl M, Shen W, Fu FH (2007) Osseous landmarks of the femoral attachment of the anterior cruciate ligament: an anatomic study. Arthroscopy 23(11):1218–1225
6. Fu FH (2011) Double-bundle ACL reconstruction. Orthopedics 34(4):281–283
7. Harner CD, Baek GH, Vogrin TM et al (1999) Quantitative analysis of human cruciate ligament insertions. Arthroscopy 15(7):741–749
8. Iriuchishima T, Tajima G, Ingham SJ et al (2009) Intercondylar roof impingement pressure after anterior cruciate ligament reconstruction in a porcine model. Knee Surg Sports Traumatol Arthrosc 17(6):590–594
9. Iriuchishima T, Tajima G, Shirakura K et al (2011) In vitro and in vivo AM and PL tunnel positioning in anatomical double bundle anterior cruciate ligament reconstruction. Arch Orthop Trauma Surg 131(8):1085–1090
10. Iriuchishima T, Ingham SJ, Tajima G et al (2010) Evaluation of the tunnel placement in the anatomical double-bundle ACL reconstruction: a cadaver study. Knee Surg Sports Traumatol Arthrosc 18(9):1226–1231
11. Iriuchishima T, Tajima G, Ingham SJ, Shen W, Smolinski P, Fu FH (2010) Impingement pressure in the anatomical and non anatomical anterior cruciate ligament reconstruction: a cadaver study. Am J Sports Med 38(8):1611–1617
12. Iriuchishima T, Horaguchi T, Kubomura T, Morimoto Y, Fu FH (2011) Evaluation of the intercondylar roof impingement after anatomical double-bundle anterior cruciate ligament reconstruction using 3D-CT. Knee Surg Sports Traumatol Arthrosc 19(4): 674–679
13. Karlsson J, Irrgang JJ, van Eck CF, Samuelsson K, Mejia HA, Fu FH (2011) Anatomic single- and double-bundle anterior cruciate ligament reconstruction. Part 2: clinical application of surgical technique. Am J Sports Med 39(9):2016–2026
14. Kondo E, Yasuda K, Azuma H, Tanabe Y, Yagi T (2008) Prospective clinical comparisons of anatomic double-bundle versus single-bundle anterior cruciate ligament reconstruction procedures in 328 consecutive patients. Am J Sports Med 36(9):1675–1687
15. Kopf S, Musahl V, Tashman S, Szczodry M, Shen W, Fu FH (2009) A systematic review of the femoral origin and tibial insertion morphology of the ACL. Knee Surg Sports Traumatol Arthrosc 17(3):213–219
16. Kopf S, Pombo MW, Szczodry M, Irrgang JJ, Fu FH (2011) Size variability of the human anterior cruciate ligament insertion sites. Am J Sports Med 39(1):108–1013
17. Loh JC, Fukuda Y, Tsuda E, Steadman RJ, Fu FH, Woo SL (2003) Knee stability and graft function following anterior cruciate ligament reconstruction: comparison between 11 o'clock and 10 o'clock femoral tunnel placement. Arthroscopy 19(3):297–304
18. Luites JW, Wymenga AB, Blankevoort L et al (2007) Description of the attachment geometry of the anteromedial and posterolateral bundles of the ACL from arthroscopic perspective for anatomical tunnel placement. Knee Surg Sports Traumatol Arthrosc 15(12): 1422–1431
19. Maeyama A, Hoshino Y, Debandi A et al (2011) Evaluation of rotational instability in the anterior cruciate ligament deficient knee using triaxial accelerometer: a biomechanical model in porcine knees. Knee Surg Sports Traumatol Arthrosc 19(8): 1233–1238
20. Muneta T, Koga H, Mochizuki T et al (2007) A prospective randomized study of 4-strand semitendinosus tendon anterior cruciate ligament reconstruction comparing single-bundle and double bundle techniques. Arthroscopy 23(6):618–628
21. Muneta T, Takakuda K, Yamamoto H (1997) Intercondylar notch width and its relation to the configuration and cross-sectional area of the anterior cruciate ligament. A cadaveric knee study. Am J Sports Med 25(1):69–72
22. Niki Y, Matsumoto H, Hakozaki A, Kanagawa H, Toyama Y, Suda Y (2011) Anatomic double-bundle anterior cruciate ligament reconstruction using bone-patellar tendon-bone and gracilis tendon graft: a comparative study with 2-year follow-up results of semitendinosus tendon grafts alone or semitendinosus-gracilis tendon grafts. Arthroscopy 27(9):1242–1251
23. Okada E, Matsumoto M, Ichihara D et al (2011) Cross-sectional area of posterior extensor muscles of the cervical spine in asymptomatic subjects: a 10-year longitudinal magnetic resonance imaging study. Eur Spine J 20(9):1567–1573
24. Shin SH, Jeon IH, Kim HJ et al (2010) Articular surface area of the coronoid process and radial head in elbow extension: surface ration in cadavers and a computed tomography in vivo. J Hand Surg Am 35(7):1120–1125
25. Shino K, Nakata K, Nakamura N et al (2008) Rectangular tunnel double-bundle anterior cruciate ligament reconstruction with bone-patellar tendon-bone graft to mimic natural fiber arrangement. Arthroscopy 24(10):1178–1183
26. Siebold R, Ellert T, Metz S et al (2008) Femoral insertions of the anteromedial and posterolateral bundles of the anterior cruciate ligament: morphometry and arthroscopic orientation models for double-bundle bone tunnel placement-a cadaver study. Arthroscopy 24(5):585–592
27. Siebold R, Ellert T, Metz S et al (2008) Tibial insertions of the anteromedial and posterolateral bundles of the anterior cruciate ligament: morphometry, arthroscopic landmarks, and orientation model for bone tunnel placement. Arthroscopy 24(2):154–161
28. Steiner ME, Murray MM, Rodeo SA (2008) Strategies to improve anterior cruciate ligament healing and graft placement. Am J Sports Med 36(1):176–189
29. Stijak L, Randonjic V, Nikolic V, Blagojevic Z, Aksic M, Filipovic B (2009) Correlation between the morphometric parameters of the anterior cruciate ligament and the intercondylar width: gender and age difference. Knee Surg Sports Traumatol Arthrosc 17:812–817
30. Takahashi M, Doi M, Abe M et al (2006) Anatomical study of the femoral and tibial insertions of the anteromedial and posterolateral bundles of human anterior cruciate ligament. Am J Sports Med 34(5):787–792
31. Tompkins M, Ma R, Hogan MV, Miller MD (2011) What's new in sports medicine. J Bone Joint Surg Am 93(8):789–797
32. van Eck CF, Kopf S, van Dijk CN, Fu FH, Tashman S (2011) Comparison of 3-dimensional notch volume between subjects with and subjects without anterior cruciate ligament rupture. Arthroscopy 27:1235–1241
33. van Eck CF, Martins CA, Vyas SM, Celentano U, van Dijk CN, Fu FH (2010) Femoral intercondylar notch shape and dimensions in ACL-injured patients. Knee Surg Sports Traumatol Arthosc 18:1257–1262
34. Wolters F, Vrooijink SH, Van Eck CF, Fu FH (2011) Does notch size predict ACL insertion site size? Knee Surg Sports Traumatol Arthrosc 19:S17–S21

35. Wu E, Chen M, Cooperman D, Victoroff B, Goodfellow D, Farrow LD (2011) No correlation of height or gender with anterior cruciate ligament footprint size. J Knee Surg 24:39–43
36. Yagi M, Wong EK, Kanamori A, Debski RE, Fu FH, Woo SL (2002) Biomechanical analysis of anatomic anterior cruciate ligament reconstruction. Am J Sports Med 30(5):660–666
37. Yasuda K, Kondo E, Ichiyama H, Tanabe Y, Tohyama H (2006) Clinical evaluation of anatomic double-bundle anterior cruciate ligament reconstruction procedure using hamstring tendon grafts: comparisons among three different procedures. Arthroscopy 22(3): 240–251
38. Yasuda K, van Eck CF, Hoshino Y, Fu FH, Tashman S (2011) Anatomic single-and double-bundle anterior cruciate ligament reconstruction. Part 1: basic science. Am J Sports Med 39(8): 1789–1799
39. Zantop T, Wellmann M, Fu FH, Peterson W (2008) Tunnel positioning of anteromedial and posterolateral bundles in anatomic anterior cruciate ligament reconstruction: anatomic and radiographic findings. Am J Sports Med 36(1):65–72