OTSR

Original article

Intraarticular lengths of double-bundle grafts can change during knee flexion: Intraoperative measurements in anatomic anterior cruciate ligament reconstructions

Takayuki Furumatsu(1, 2, 3)*, Takaaki Hiranaka(1, 2), Yuya Kodama(1), Yusuke Kamatsuki(1), Yuki Okazaki(1), Tadashi Yamawaki(1, 3), Hirosuke Endo(1), Toshifumi Ozaki(1)

1) Department of Orthopaedic Surgery, Okayama University Hospital, 2-5-1 Shikatacho, Kitaku, Okayama 700-8558, Japan
2) Department of Orthopaedic Surgery, Sumitomo Besshi Hospital, 3-1 Oujicho, Niihama, Ehime 792-8543, Japan
3) Department of Orthopaedic Surgery, Kousei Hospital, 3-8-35 Kouseicho, Kitaku, Okayama 700-0985, Japan

* Corresponding to: Dr. Takayuki Furumatsu, Department of Orthopaedic Surgery, Okayama University Hospital, 2-5-1 Shikatacho, Kitaku, Okayama 700-8558, Japan
Tel: 81-86-235-7273; Fax: 81-86-223-9727; E-mail: matino@md.okayama-u.ac.jp

Abstract

Background: The lengths of the anteromedial bundle (AMB) and posterolateral bundle (PLB) change during knee motion during double-bundle anterior cruciate ligament (ACL) reconstruction. However, the actual intraarticular graft length would be affected by the bone tunnel position and tunnel creation angle during ACL reconstruction. The aim of this study was to investigate the intraarticular length change of the AMB and PLB in patients who underwent anatomic double-bundle ACL reconstruction.

Hypothesis: We hypothesized that the PLB would show a more dynamic length change pattern than the AMB during knee flexion at ACL reconstruction.

Methods: Thirty-two patients (16 men and 16 women) who had isolated ACL injuries with intact menisci were investigated. Anatomic double-bundle ACL reconstructions were performed using semitendinosus tendon autografts at a mean age of 30.6 years. The graft and tunnel lengths were measured intraoperatively. Intraarticular graft lengths and length changes were calculated at 0˚ and 90˚ of knee flexion during ACL reconstruction. Intraoperative data were collected prospectively, and analyses were performed retrospectively.

Results: The intraarticular length of the AMB at 0˚ of knee flexion was 28.1 ± 5.5 mm. At 90˚ of knee flexion, the AMB intraarticular length decreased to 25.6 ± 4.8 mm. The intraarticular length of the PLB decreased to 17.7 ± 4.6 mm at 90˚ of knee flexion compared to 22.0 ± 4.2 mm at 0˚ of knee flexion. Changes in the intraarticular graft length during knee flexion were detected more in the PLB (4.1 mm) than in the AMB (2.0 mm, $P = 0.01$).

Discussion: This study demonstrated that the intraarticular length change of the PLB during knee motion was

larger than that of the AMB in anatomic double-bundle ACL reconstructions with semitendinosus tendon autografts and suspensory femoral fixation devices.

Level of evidence: IV: retrospective cohort study

Keywords: Anterior cruciate ligament, anatomic double-bundle reconstruction, intraarticular length, semitendinosus autograft

Running title: Intraarticular length changes of double-bundle grafts

Abbreviations:

ACL, anterior cruciate ligament

AMB, anteromedial bundle

CT, computed tomography

PLB, posterolateral bundle

1. Introduction

Anterior cruciate ligament (ACL) reconstruction using a tendinous autograft can effectively restore abnormal knee kinematics in ACL-deficient knees. Anatomic studies report that the ACL length ranges from 22 to 44 mm (mean, 32 mm) and its width ranges from 7 to 12 mm [1]. Functionally, the ACL is divided into two major fiber bundles, the anteromedial bundle (AMB) and the posterolateral bundle (PLB) [2]. This two-bundle model has been accepted as simple representation to understand ACL function. The double-bundle ACL reconstruction seems to be clinically superior to conventional single-bundle ACL reconstruction with regard to knee stability and vertical jump performance [3]. On the other hand, Adravanti et al. demonstrated that no advantages are observed in postoperative clinical outcomes and knee stability using double-bundle ACL reconstruction [4]. The flat ribbon-like structure of the ACL is also accepted as a reasonable concept for anatomic ACL reconstruction [5, 6]. During the knee motion, the ACL fibers substituted by the AMB and PLB are not isometric. The AMB tightens during knee flexion while the PLB becomes slack [1, 7]. To successfully reproduce the intrinsic length change property of native ACL, modern anatomic ACL reconstruction techniques such as double-bundle and/or flat ribbon-like reconstructions may be superior to conventional single-bundle ACL reconstruction [8].

Cadaveric studies demonstrated that the lengths of the AMB and PLB could change during knee motion [9, 10]. The end-to-end distances of representative points for the AMB and PLB are longer in extension and shorter in flexion [9]. In this study, the distances of the AMB and PLB were 37 mm and 28 mm, respectively, at full extension and 35 mm and 21 mm, respectively, at 90° of knee flexion. However, the actual intraarticular graft length is affected by the bone tunnel position, tunnel creation angle, tunnel diameter, graft shift, tibial rotation, and meniscal status in ACL reconstruction [10-14]. In addition, the exact length of the tendinous autograft rarely stretches under physiological loading conditions because of its condensed collagen fiber structure [15]. Deleterious graft elongations after ACL reconstruction, leading to unexpected knee instabilities, seem to be primarily caused by adjustable loop fixation devices, graft preparation, and graft conditioning [15-18]. The aim of this study was to investigate the intraarticular length change of both the AMB and PLB in patients who underwent anatomic double-bundle ACL reconstruction. We hypothesized that the PLB would show a more dynamic graft sliding in the tibial tunnel than the AMB during knee flexion at the time of anatomic double-bundle ACL reconstruction.

2. Materials & methods

Between November 2018 and September 2019, 32 consecutively recruited patients who had isolated ACL injuries without meniscal tears, severe chondral damages, and/or degenerative cartilaginous lesions were enrolled (Table 1). We included the patients who showed normal/intact status of the meniscus. Patients who had concomitant meniscus injuries, degenerated menisci, and severe cartilaginous lesions were excluded (n = 57). The mean time from injury to surgery was 58 days (range, 26−81 days). Medical records were reviewed retrospectively to examine the age, sex, height, body weight, and body mass index. Intraoperative data were collected prospectively and analysis was performed retrospectively. This study was a multicenter study and received the approval of our Institutional Review Board (No. 1506-018), and was performed in accordance with the ethical standards as laid down in the 1964 Declaration of Helsinki and its later amendments. Written informed consent was obtained from all participants. Patient demographics are shown in Table 1.

2.1. Surgical procedure and length measurement

Routine arthroscopic evaluation was performed before ACL reconstructions. A remnant of the torn ACL fibers was removed except for the native ACL tibial attachment. Minimal ablation and/or tibial stump preservation techniques were used to avoid iatrogenic injuries of the lateral meniscus anterior root attachment [19]. Anatomic double-bundle ACL reconstructions were performed using semitendinosus tendon autografts. One experienced surgeon performed arthroscopic procedures. A semitendinosus tendon was transversely cut into two portions, and each portion was folded over as a 2-stranded tendon graft. The tendon was sutured together to form a closed loop with 6 Krackow locking stitches (No. 3 Ethibond, Ethicon, Somerville, NJ, USA) for the tibial tunnel side. An Endobutton CL BTB fixation device (Smith & Nephew, Andover, MA, USA) was used for the femoral tunnel side through the tendon loop. Pre-tensioning was performed to avoid graft elongation in the stitched portion as described [15]. A continuous load of 70 N was applied to the prepared graft fourth for 30 sec each on a graft board. A final length of the graft was measured precisely using a ruler. A diameter of each graft end was measured by a metal cylindrical tube with a 0.5-mm interval. The graft diameter of the tibial tunnel side had the same size or larger size compared with that of the femoral tunnels side.

Two femoral tunnels and two tibial tunnels were created within the native ACL footprints using an outside-in technique for the AMB and PLB [19-21]. Tibial tunnels for the PLBs were placed nearby the medial tibial eminence, just posterior to the AMB tibial tunnels, according to the tibial C-shaped insertion concept [22]. A 2.4-mm guide wire was drilled into the bone using Acufex pinpoint anatomic ACL guide system (Smith & Nephew). The tips of each guide wire were set at the intra-articular surface of the bone. Then, each tunnel length was measured using a tunnel depth gauge. Bone tunnels were created using a reamer that was adjusted to each graft end diameter at the femoral and tibial tunnel sides (between 4.5 and 7.0 mm). A length of Endobutton CL BTB was determined by a graft setting with the intra-femoral tunnel length ≥ 15 mm. The intra-femoral tunnel length of the graft was calculated using the femoral tunnel length and Endobutton CL BTB length. Firstly, a graft for the PLB was pulled up through the tibial tunnel, intra-articular space, and the femoral tunnel. Secondary, the AMB graft was set same as the PLB graft.

Following the graft passing, a pre-conditioning was performed by 5-times of knee flexion-extension motion (0°−120°) under a 20-N tension-applied condition for the tibial graft suture ends. The knee flexion angles were determined manually using a goniometer. At 0° and 90° of knee flexion, a cavity length of each tibial tunnel was measured by a small depth gauge, with 5-N tension to the threads. The cavity length was defined as the distance between the intra-tibial graft end and the tunnel aperture center on the anterior tibial surface (Fig. 1). A second-time measurement of the cavity length was performed by the other observer after an additional knee flexion-extension motion. These procedures repeated twice. A mean of 4 measurement values (2 measurements in each observer) was used as the cavity length. The graft length surrounded in the tibial tunnel was calculated using the tibial tunnel length and a mean of the cavity length. An intraarticular length of the graft was calculated using prepared graft length, intra-femoral tunnel length, and intra-tibial tunnel length at 0° and 90° of knee flexion. Then, changes in intraarticular length of the AMB and PLB were determined.

2.2. Evaluations of bone tunnel positions

Computed tomography (CT) images were obtained with an Asteion 4 Multislice CT system (Toshiba Medical Systems, Tochigi, Japan) using 120 kVp and 150 mA, and 1-mm slice thickness at 1 week postoperatively. Three-dimensional CT images of the femur and tibia were reconstructed using a three-dimensional volume-rendering technique (AZE Virtual Place software, Tokyo, Japan). The lateral wall of the femoral intercondylar notch and the tibial surface were visualized (Fig. 2). The position of each tunnel aperture center was evaluated with a quadrant method using a rectangular measurement grid [19]. On the femoral side, a measurement grid was set along the Blumensaat's line, with a condition that the rectangular box covered the lateral wall. The location of the femoral tunnel aperture was determined as a percentage of the distance both parallel (the deep-to-shallow direction) and perpendicular (the high-to-low direction) to the Blumensaat's line. On the tibial side, a measurement grid was set along a tangential line that touched the posterior margin of both medial and lateral tibial plateaus. Each border of the rectangular box was set at the anterior, medial, and lateral margins of the tibial surface. The location of the tibial tunnel aperture was determined as a percentage of the anteroposterior and mediolateral dimensions. No patients were lost during the short-term follow-up period. Two orthopedic surgeons (TH and YO) independently measured the central position of the bone tunnel apertures in a blinded manner. Each observer performed each measurement twice, at least two weeks apart. An average value derived from the four measurement values as the position of each tunnel center. The inter-observer and intra-observer reliabilities were assessed with the intra-class correlation coefficient (ICC). An ICC of > 0.80 was considered to represent a reliable measurement.

2.3. Statistical analysis

The Mann-Whitney *U* test was used to compare the variables. Linear regression analysis was used to assess the correlations among the indicated values. Power and statistical analyses were performed using EZR-WIN software (Saitama Medical Center, Saitama, Japan). Data are presented as the mean ± standard deviation. Significance was set at $P < 0.05$.

3. Results

The intraarticular length change of the PLB (4.1 mm) was larger than that of the AMB (2.0 mm) during intraoperative knee motion ($P = 0.010$). The femoral and tibial tunnel lengths for the AMB and PLB are shown in Table 2. The means of the tunnel diameter of the AMB and PLB are also shown in Table 2. The prepared graft lengths of the AMB and PLB were 65.8 ± 3.1 mm and 55.9 ± 5.9 mm, respectively ($P < 0.001$). Intraarticular length of the AMB at 0˚ knee flexion (28.1 ± 5.5 mm) was greater than that at 90˚ of knee flexion (25.6 ± 4.8 mm), with 5-N tension to the threads (Fig. 3, $P = 0.044$). Intraarticular length of the PLB decreased to 17.7 ± 4.6 mm at 90˚ of knee flexion compared to 22.0 ± 4.2 mm at 0˚ of knee flexion (Fig. 3, $P = 0.003$). Changes in intraarticular length of the AMB and PLB were 2.0 ± 1.7 mm and 4.1 ± 3.3 mm, respectively. The intraarticular length change of the PLB during knee motion was larger than that of the AMB ($P = 0.010$).

Femoral tunnel apertures of the AMB were localized at 28.3 ± 6.6% in the high-to-low direction and 22.1 ± 3.2% in the deep-to-shallow direction using the three-dimensional CT-based quadrant method

(Fig. 4A). The positions of the PLB femoral tunnels and tibial tunnel apertures are shown in Fig. 4 (4B-D). In a linear regression analysis, no significant correlation was observed between the intraarticular graft length and each tunnel position (*P* values, n.s.). Regarding the measurement of bone tunnel location, the ICCs for inter-observer and intra-observer reliabilities were 0.84 and 0.88, respectively.

4. Discussion

The most important finding of this study was that the intraarticular length change of the PLB during intraoperative knee motion was larger than that of the AMB at anatomic double-bundle ACL reconstructions with semitendinosus tendon autografts and suspensory femoral fixation devices. Our hypothesis “the PLB would show a more dynamic length change pattern than the AMB during knee flexion at ACL reconstruction” was confirmed. Several authors have described that anatomic ACL reconstructions are non-isometric [10, 23, 24]. A three-dimensional CT-based analysis demonstrates that a virtual PLB shows a mean of 7.6-mm length change during knee flexion from 0° to 90° using the point-to-point measurement method [23]. On the other hand, a virtual AMB has a mean of 4.6-mm decrease in its length at 90° of knee flexion compared to the AMB length at 0° of knee flexion. A biomechanical study using cadaveric knees demonstrated that a PLB-like graft setting shows an approximately 6-mm decrease in the graft length during knee flexion from 0° to 90° [10]. An AMB-like graft setting shows an approximately 3-mm decrease in the graft length during knee flexion from 0° to 90°. These findings support the validity of our measurement method in determining the intraarticular length of each bundle at anatomic double-bundle ACL reconstructions with semitendinosus autografts and suspensory femoral fixation devices.

The native ACL has an intrinsic length change of 3−6 mm. Cadaveric studies have described that the graft length changes during knee motion even though tunnel apertures are created within the femoral and tibial attachments of the native ACL [10, 24]. However, property and viability in tendinous grafts are different between a fresh-frozen tendinous graft including tendon allograft and a freshly prepared semitendinosus autograft [25, 26]. In our study, a fixed loop suspensory device was used for femoral fixation. Several authors have reported that fixed loop devices would have a potential risk of tunnel widening following ACL reconstruction using hamstring grafts [27, 28]. Fixed loop devices can also induce semitendinosus tendon graft shifts within bone tunnels in the direction of the tension applied to the graft during knee range of motion [12]. In addition, the position of the tunnel centers seems to be dependent on each surgeon or institute even if the tunnels are created within the native ACL footprint during anatomic ACL reconstruction [29]. The combination of femoral and tibial tunnel apertures can affect the length change pattern of each graft. We consider that it is important to recognize the length change pattern of double-bundle semitendinosus autografts for individual surgeons in their own surgical procedures. Our tunnel placement strategy demonstrated that the PLB had a 4-mm mean length change compared with a 2-mm mean length change of the AMB during knee flexion. Mutsuzaki et al. demonstrated that the PLB acts effectively against both anterior tibial load and internal tibial torque at knee extension in a goat ACL reconstruction model [30]. We consider that tibial fixation of the PLB should be performed with the knee in nearly full extension to minimize risks of PLB failure by excessive graft stretching and knee extension loss [9, 24].

This study has several limitations. The effect of the tunnel creation angle on the graft length change was not assessed. The actual length change pattern of each graft was not investigated following the final tibial fixation. An anterior tibial translation might affect the change in tibial tunnel cavity length during intraoperative measurements. Our measurement method evaluated graft sliding in the tibial tunnel but did not assess the actual distance between tunnel centers. Internal and external rotations of the tibia were not considered during manually applied knee motion. Measurements at several knee flexion angles (30° and 60°) under controlled rotational forces may be required to understand the precise length change pattern during ACL reconstruction. In addition, it was difficult to measure the graft tension or in situ force concurrently with the graft shift during ACL reconstruction.

5. Conclusions

The intraarticular length change of the PLB was larger than that of the AMB at anatomic double-bundle ACL reconstructions with semitendinosus tendon autografts and suspensory femoral fixation devices during knee motion.

Acknowledgments

We are grateful to Drs. Shinichi Miyazawa, Takaaki Tanaka, Hiroto Inoue, Yoshiki Okazaki, and Shin Masuda for their clinical supports. We would like to thank Editage (www.editage.com) for English language editing.

Compliance with ethical standards

Informed consent

Informed consent was obtained from all patients for being included in this study.

Funding

This study was partly supported by grants from the Stryker Academic Contribution Program (TF) and the Smith and Nephew (TF).

Disclosure of interest

The authors have no conflict of interest.

Contributions of authors

Takayuki Furumatsu designed the study, performed surgeries, and prepared the manuscript. Takaaki Hiranaka, Yuya Kodama, Yusuke Kamatsuki, Yuki Okazaki, Tadashi Yamawaki, Hirosuke Endo, and Toshifumi Ozaki contributed to the data collection. All authors contributed to the analysis and interpretation of data. All authors critically reviewed the manuscript and approved the final version of the manuscript.

References

1. Amis AA, Dawkins GPC. Functional anatomy of the anterior cruciate ligament. Fibre bundle actions related to ligament replacements and injuries. J Bone Joint Surg 1991;73(B):260–7.
2. Girgis FG, Marshall JL, Monajem ARSA. The cruciate ligaments of the knee joint. Anatomical,

functional and experimental analysis. Clin Orthop 1975;106:216–31.

3. Ventura A, Iori S, Legnani C, Terzaghi C, Borgo E, Albisetti W. Single-bundle versus double-bundle anterior cruciate ligament reconstruction: assessment with vertical jump test. Arthroscopy 2013;29:1201-10.

4. Adravanti P, Dini F, de Girolamo L, Cattani M, Rosa MA. Single-bundle versus double-bundle anterior cruciate ligament reconstruction: a prospective randomized controlled trial with 6-year follow-up. J Knee Surg 2017;30:898-904.

5. Siebold R. Flat ACL anatomy: fact no fiction. Knee Surg Sports Traumatol Arthrosc 2015;23:3133-5.

6. Śmigielski R, Zdanowicz U, Drwięga M, Ciszek B, Williams A. The anatomy of the anterior cruciate ligament and its relevance to the technique of reconstruction. Bone Joint J 2016;98-B:1020-6.

7. Duthon VB, Barea C, Abrassart S, Fasel JH, Fritschy D, Ménétrey J. Anatomy of the anterior cruciate ligament. Knee Surg Sports Traumatol Arthrosc 2006;14:204-13.

8. Hussein M, van Eck CF, Cretnik A, Dinevski D, Fu FH. Prospective randomized clinical evaluation of conventional single-bundle, anatomic single-bundle, and anatomic double-bundle anterior cruciate ligament reconstruction: 281 cases with 3- to 5-year follow-up. Am J Sports Med 2012;40:512-20.

9. Wang JH, Kato Y, Ingham SJ, Maeyama A, Linde-Rosen M, Smolinski P, Fu FH. Measurement of the end-to-end distances between the femoral and tibial insertion sites of the anterior cruciate ligament during knee flexion and with rotational torque. Arthroscopy 2012;28:1524-32.

10. Tanabe Y, Yasuda K, Kondo E, Kawaguchi Y, Akita K, Yagi T. Comparison of Graft Length Changes During Knee Motion Among 5 Different Anatomic Single-Bundle Anterior Cruciate Ligament

Reconstruction Approaches: A Biomechanical Study. Orthop J Sports Med 2019;7:2325967119834933.

11. Ebersole GM, Eckerle P, Farrow LD, Cutuk A, Bledsoe G, Kaar S. Anterior cruciate ligament graft isometry is affected by the orientation of the femoral tunnel. J Knee Surg 2016;29:260-6.
12. Fujii M, Sasaki Y, Araki D, Furumatsu T, Miyazawa S, Ozaki T, Linde-Rosen M, Smolinski P, Fu FH. Evaluation of the semitendinosus tendon graft shift in the bone tunnel: an experimental study. Knee Surg Sports Traumatol Arthrosc 2016;24:2773-7.
13. Kodama Y, Furumatsu T, Miyazawa S, Fujii M, Tanaka T, Inoue H, Ozaki T. Location of the tibial tunnel aperture affects extrusion of the lateral meniscus following reconstruction of the anterior cruciate ligament. J Orthop Res 2017;35:1625-33.
14. Okazaki Y, Furumatsu T, Miyazawa S, Kodama Y, Kamatsuki Y, Hino T, Masuda S, Ozaki T. Meniscal repair concurrent with anterior cruciate ligament reconstruction restores posterior shift of the medial meniscus in the knee-flexed position. Knee Surg Sports Traumatol Arthrosc 2019;27:361-8.
15. Fujii M, Furumatsu T, Miyazawa S, Tanaka T, Inoue H, Kodama Y, Masuda K, Seno N, Ozaki T. Features of human autologous hamstring graft elongation after pre-tensioning in anterior cruciate ligament reconstruction. Int Orthop 2016;40:2553-8.
16. Mayr R, Heinrichs CH, Eichinger M, Coppola C, Schmoelz W, Attal R. Biomechanical comparison of 2 anterior cruciate ligament graft preparation techniques for tibial fixation: adjustable-length loop cortical button or interference screw. Am J Sports Med 2015;43:1380-5.
17. Blythe A, Tasker T, Zioupos P. ACL graft constructs: In-vitro fatigue testing highlights the occurrence of irrecoverable lengthening and the need for adequate (pre)conditioning to avert the recurrence of knee

instability. Technol Health Care 2006;14:335-47.

18. Noyes FR, Huser LE, Ashman B, Palmer M. Anterior cruciate ligament graft conditioning required to prevent an abnormal Lachman and pivot shift after ACL reconstruction: A robotic study of 3 ACL graft constructs. Am J Sports Med 2019;47:1376-84.

19. Kodama Y, Furumatsu T, Hino T, Kamatsuki Y, Ozaki T. Minimal ablation of the tibial stump using bony landmarks improved stability and synovial coverage following double-bundle anterior cruciate ligament reconstruction. Knee Surg Relat Res 2018;30:348-55.

20. Furumatsu T, Fujii M, Tanaka T, Miyazawa S, Ozaki T. The figure-of-nine leg position for anatomic anterior cruciate ligament reconstruction. Orthop Traumatol Surg Res 2015;101:391-3.

21. Hiranaka T, Furumatsu T, Kamatsuki Y, Sugiu K, Okazaki Y, Masuda S, Okazaki Y, Takihira S, Miyazawa S, Nakata E, Ozaki T. Posttraumatic cartilage degradation progresses following anterior cruciate ligament reconstruction: A second-look arthroscopic evaluation. J Orthop Sci 2019;24:1058-63.

22. Siebold R, Schuhmacher P, Fernandez F, Śmigielski R, Fink C, Brehmer A, Kirsch J. Flat midsubstance of the anterior cruciate ligament with tibial "C"-shaped insertion site. Knee Surg Sports Traumatol Arthrosc 2015;23:3136-42.

23. Yoo YS, Jeong WS, Shetty NS, Ingham SJ, Smolinski P, Fu F. Changes in ACL length at different knee flexion angles: an in vivo biomechanical study. Knee Surg Sports Traumatol Arthrosc 2010;18:292-7.

24. Lubowitz JH. Anatomic ACL reconstruction produces greater graft length change during knee range-of-motion than transtibial technique. Knee Surg Sports Traumatol Arthrosc 2014;22:1190-5.

25. Bachy M, Sherifi I, Zadegan F, Petite H, Vialle R, Hannouche D. Allograft integration in a rabbit

transgenic model for anterior cruciate ligament reconstruction. Orthop Traumatol Surg Res 2016;102:189-95.

26. Bottagisio M, Pellegata AF, Boschetti F, Ferroni M, Moretti M, Lovati AB. A new strategy for the decellularisation of large equine tendons as biocompatible tendon substitutes. Eur Cell Mater 2016;32:58-73.

27. Saccomanno MF, Shin JJ, Mascarenhas R, Haro M, Verma NN, Cole BJ, Bach BR Jr. Clinical and functional outcomes after anterior cruciate ligament reconstruction using cortical button fixation versus transfemoral suspensory fixation: a systematic review of randomized controlled trials. Arthroscopy 2014;30:1491-8.

28. Choi NH, Yang BS, Victoroff BN. Clinical and radiological outcomes after hamstring anterior cruciate ligament reconstructions: comparison between fixed-loop and adjustable-loop cortical suspension devices. Am J Sports Med 2017;45:826-31.

29. Song EK, Kim SK, Lim HA, Seon JK. Comparisons of tunnel-graft angle and tunnel length and position between transtibial and transportal techniques in anterior cruciate ligament reconstruction. Int Orthop 2014;38:2357-62.

30. Mutsuzaki H, Fujie H, Nakajima H, Fukagawa M, Nomura S, Sakane M. Comparison of postoperative biomechanical function between anatomic double-bundle and single-bundle ACL reconstructions using calcium phosphate-hybridized tendon grafts in goats. Orthop Traumatol Surg Res 2017;103:239-43.

Table 1. Patient demographics

		Range
Number of patients	32	
Gender, men/women	16/16	
Age, years	30.6 ± 12.5	15 – 57
Body mass index, kg/m^2	24.1 ± 4.2	18.0 – 36.7

Data of age and body mass index are displayed as a mean ± standard deviation.

Table 2. Intraoperative measurements

	Anteromedial bundle	Posterolateral bundle	*P* value
Femoral tunnel length, mm	39.6 ± 5.6	39.5 ± 4.5	0.474
Femoral tunnel diameter, mm	5.7 ± 0.6	5.0 ± 0.6	< 0.001*
Tibial tunnel length, mm	41.6 ± 5.6	41.3 ± 4.4	0.423
Tibial tunnel diameter, mm	6.1 ± 0.6	5.6 ± 0.6	0.001*
Graft length, mm	65.8 ± 3.1	55.9 ± 5.9	< 0.001*
Intraarticular length, mm (0˚ flexion)	28.1 ± 5.5	22.0 ± 4.2	< 0.001*
Intraarticular length, mm (90˚ flexion)	25.6 ± 4.8	17.7 ± 4.6	< 0.001*
Change in intraarticular length, mm (0˚ − 90˚ flexion intraarticular length)	2.0 ± 1.7	4.1 ± 3.3	0.010*

Data are displayed as a mean ± standard deviation. * $P < 0.05$

Figure legends

Fig. 1. Measurements of tunnel and intraarticular graft lengths. Red and blue cylindrical columns denote the graft passing route for the AMB and PLB. Double-headed arrows, femoral tunnel length. Dotted double-headed arrows, tibial tunnel length. The intraarticular length was calculated using the cavity length (dashed arrow) of each tibial tunnel.

Fig. 2. Three-dimensional CT images following anatomic double-bundle ACL reconstruction. (A) Femoral tunnel positions. (B) Tibial tunnel apertures. The blue boxes denote the measurement grids. The red arrows indicate the measurement directions. Bars, 1 cm.

Fig. 3. Intraarticular graft lengths at 0˚ and 90˚ of knee flexion angles. $*P < 0.05$.

Fig. 4. Position of each tunnel aperture center. Femoral tunnel positions of the AMB (A, 28.3 ± 6.6% in the high-to-low and 22.1 ± 3.2% in the deep-to-shallow direction) and PLB (B, 53.1 ± 5.3% and 34.3 ± 4.6% in each direction). Filled circles denote the mean position of each femoral tunnel. Tibial tunnel positions of the AMB (C, 29.6 ± 5.1% in the anteroposterior direction and 44.3 ± 2.4% in the mediolateral direction) and PLB (D, 45.0 ± 5.9% and 45.7 ± 1.9% in each direction). Filled triangles indicate the mean position of each tibial tunnel.