

Is the Grafted Tendon Shifted Anteriorly in the Femoral Tunnel at the Postremodeling Phase After Anterior Cruciate Ligament Reconstruction?

A Clinical MRI Study

Jun Onodera,* MD, PhD, Kazunori Yasuda,*^{†‡} MD, PhD, Tetsuro Masuda,* MD, PhD, Yoshie Tanabe,* PhD, RPT, Nobuto Kitamura,* MD, PhD, Tomonori Yagi,[†] MD, PhD, and Eiji Kondo,[§] MD, PhD

Investigation performed at the Department of Sports Medicine, Hokkaido University Graduate School of Medicine, Sapporo, Japan

Background: Based on previous in vitro studies, it has been commonly believed that during anterior cruciate ligament (ACL) reconstruction with hamstring tendon, the grafted tendon is shifted anteriorly in the tunnel permanently after the graft is anchored to the tunnel wall. However, this has not been proven by in vivo studies.

Hypothesis: At 1 year after anatomic double-bundle ACL reconstruction, the grafted tendons may not be shifted anteriorly in the femoral tunnel but anchored to the bony wall at the center of the tunnel.

Study Design: Case series; Level of evidence, 4.

Methods: Participants consisted of 40 patients who underwent anatomic double-bundle ACL reconstruction. The grafted tendons located in the femoral tunnel were examined 1 year after surgery using 2 different magnetic resonance imaging (MRI) protocols. In the first substudy, with 20 patients, the grafted tendon location was evaluated on an inclined sagittal multiplanar reconstruction (MPR) image taken using a standard T2-weighted protocol. In the second substudy with the remaining 20 patients, tendon location was evaluated on a pure axial MPR image taken using a VISTA (volume isotropic turbo spin echo acquisition) protocol.

Results: On the inclined sagittal T2-weighted images of the anteromedial (AM) graft, the anterior width of the newly formed fibrous tissue, which surrounded the tendon graft, was significantly greater than the posterior width ($P = .001$). The center of the grafted tendon was slightly (mean, 2.5% of the tunnel diameter) but significantly ($P = .0310$) shifted posteriorly from the tunnel center. On the axial T2-VISTA images, the center of the AM graft was slightly but significantly shifted posteriorly (3.9%; $P = .022$) and medially (5.5%; $P = .002$) from the tunnel center. The center of the posterolateral (PL) graft was not significantly shifted to any direction from the center of the tunnel.

Conclusion: The grafted tendons were not shifted anteriorly in the femoral tunnel 1 year after anatomic double-bundle ACL reconstruction. The PL graft was located approximately at the center of the tunnel outlet, while the AM graft was slightly but significantly shifted posteriorly and proximally.

Keywords: anterior cruciate ligament; double-bundle reconstruction; MRI; grafted tendon location; femoral tunnel, intraosseous graft healing

The cortical suspensory fixation method, in which a hamstring tendon grafted in the femoral tunnel is tethered to the cortical bone of the lateral femoral condyle

using a button with a polyester continuous loop, has been commonly used in various anterior cruciate ligament (ACL) reconstruction procedures. In these procedures, the grafted tendon is acutely bent at the edge of the femoral tunnel outlet toward the anterior direction, when the knee is extended after surgery. Previous studies with cadaveric knees have shown that the grafted

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tendon is shifted anteriorly in the bone tunnel immediately after surgery with this fixation method, contacting with the anterior wall of the tunnel outlet.^{7,23,26,33} Therefore, it has been a common belief in the clinical field that the grafted tendon may shift anteriorly in the femoral tunnel permanently after the graft is anchored to the tunnel wall. Recently, this anterior-shift phenomenon of the grafted tendon has been regarded as a non-negligible matter in determining the femoral tunnel location in double-bundle ACL reconstruction, because precise graft implantation into the center of the anteromedial (AM) or posterolateral (PL) bundle attachment is considered to be the most critical factor to obtain excellent clinical results in this procedure.^{20,34,36,39} To solve this problem, some surgeons have recommended that each femoral tunnel should not be created at the center of the AM or PL bundle attachment, but created at a point more posteriorly to the attachment center, taking the anterior-shift phenomenon into account.^{7,17} However, no studies have reported on where the grafted tendon is located in the tunnel during the postremodeling phase after ACL reconstruction. Previous canine model studies clarifying the bonding mechanism of the grafted tendon in the bone tunnel^{32,35} have shown that the grafted tendon was located approximately at the center of the tunnel at 6 and 12 weeks after ACL reconstruction and that it was firmly bonded to the tunnel wall with newly formed fibrous tissues. Therefore, we have realized the need to conduct a clinical study to clarify whether the grafted tendon remains shifted anteriorly in the femoral tunnel after the graft is anchored to the tunnel wall.

To answer this question, we conducted a descriptive laboratory study with a new magnetic resonance imaging (MRI) technology, using patients who have undergone anatomic double-bundle ACL reconstruction. In this study, we had 2 hypotheses: First, the 2 grafted tendons may not be shifted anteriorly in each femoral tunnel at the 1-year period after surgery. Second, the grafted tendons may be surrounded by the newly formed fibrous tissue, and located at the center of each femoral tunnel at the 1-year period.

METHODS

Study Design

A descriptive laboratory study was conducted using a total of 40 consecutive patients who underwent an arthroscopic second-look examination after ACL reconstruction between April 2012 and March 2015. All the

patients had undergone anatomic double-bundle ACL reconstruction with hamstring tendon autografts approximately 1 year before. This study was composed of 2 sub-studies with 20 patients each.

According to the study design described below, which was accepted by the institutional review board in our hospital, we asked the patients to take part in this study and to undergo an MRI examination of the ACL-reconstructed knee. Then, they were informed that they could elect not to take part in this study. All 40 patients agreed to undergo the MRI examination.

The substudy 1 was conducted to make standard observations of the grafted tendon and the other structures in the knee joint, using the first 20 consecutive patients. MRI of the ACL-reconstructed knee was performed with a 3.0-T whole-body clinical scanner (Discovery MR 750W, GE Healthcare Japan) using a standard T2-weighted protocol (the parameters used are shown in Appendix 1). This protocol could evaluate the quality of the tendon graft located in the joint cavity in the longitudinal plane.^{6,22} The substudy 2, with the remaining 20 patients, was performed with a 3.0-T whole-body clinical scanner (Achieva TX-series; Philips Healthcare). To more clearly distinguish the fibrous tissue newly formed in the bone tunnel from the grafted tendon, we used a 3-dimensional (3D) fast spin-echo (FSE) intermediate-weighted MRI sequence (volume isotropic turbo spin-echo acquisition [VISTA]) (the parameters used are shown in Appendix 1), based on recent MRI studies.^{13,30,40}

In each substudy, the anonymized DICOM (digital imaging and communications in medicine) data were converted to multiplanar reconstruction (MPR) images and reviewed on a monitor display, using the 3D DICOM Viewer software (zioTerm2009, Ziosoft Inc; see Appendix 2). Then, on the monitor display, a researcher determined the inclined coronal and sagittal sections on which the long axis of the femoral tunnel existed, as well as the axial section at the tunnel outlet level, which was perpendicular to the long axis (Figure 1).

After the MRI examination, clinical evaluations and arthroscopic examinations were performed on all patients to assess whether the reconstructed ACL was functioning. Additionally, we retrospectively evaluated femoral tunnel widening in each knee using computed tomography (CT) images. The images were taken in our hospital at 2 weeks and approximately 1 year after surgery, using a 64-slice multidetector CT (Aquilion 64; Toshiba Medical Systems). The CT images were processed using the zioTerm2009 software. The 0.5-mm sections were secondarily reconstructed with a bony algorithm to allow multiplanar reconstructions (1-mm thickness per 1-mm interval) from the axial data set.

†Address correspondence to Kazunori Yasuda, MD, PhD, Department of Sports Medicine, Hokkaido University Graduate School of Medicine, Kita-15 Nishi-7, Kita-ku, Sapporo, 060-8638, Japan (email: yasukaz@med.hokudai.ac.jp).

*Department of Sports Medicine, Hokkaido University Graduate School of Medicine, Sapporo, Japan.

†Research Center for Knee Surgery, Yagi Orthopaedic Hospital, Sapporo, Japan.

§Department of Advanced Therapeutic Research for Sports Medicine, Hokkaido University Graduate School of Medicine, Sapporo, Japan.

The authors declared that they have no conflicts of interest in the authorship and publication of this contribution.

Ethical approval for this study was obtained from Hokkaido University Hospital, Sapporo, Japan.

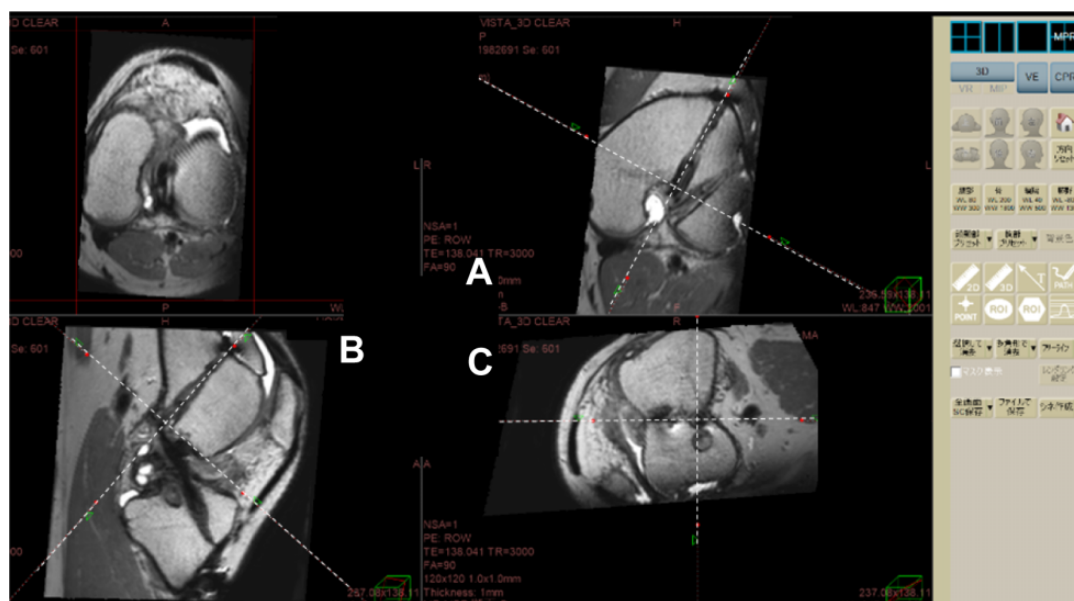


Figure 1. Multiplanar reconstruction images shown on a monitor display. A researcher simultaneously observed 3 images (A, B, and C) that showed 3 orthogonal plane sections of the knee. In each section image, the other 2 orthogonal section planes were shown as 2 lines crossing (dashed white lines). The researcher first decided the inclined coronal and sagittal sections, moving the X-Y-Z coordinates so that each section was parallel to the long axis of the femoral tunnel (A and B). Then, a pure axial image of the femoral tunnel was automatically shown on the display. Finally, the researcher decided the axial section level that was the closest to the intra-articular tunnel outlet (C).

Patient Demographics

The patients in substudy 1 included 11 men and 9 women with a mean age of 25.4 years at the time of surgery, and those in substudy 2 included 9 men and 11 women with a mean age of 27.3 years at the time of surgery. Each patient had been diagnosed with an isolated ACL tear and had undergone ACL reconstruction with the anatomic double-bundle procedure. The period after surgery ranged from 12 to 18 months in all patients. Concerning the body height and weight of the patients, there were no significant difference between the subgroups (Table 1). The contralateral knee in each patient was healthy and free of previous injury. The MRI examination did not show any injuries in the menisci or cartilage.

Surgical Procedure and Postoperative Management

The details of the anatomic procedure have been previously described (Figure 2).^{14,37,38} In the double-bundle procedure, the AM graft diameter ranged from 6 to 6.5 mm (mean \pm SD, 6.3 \pm 0.3 mm), and the PL graft diameter ranged from 5.5 to 6 mm (mean \pm SD, 5.8 \pm 0.2 mm).

Postoperative management was performed using our original rehabilitation protocol.¹⁹ A postoperative immobilizer was applied for 2 weeks after the operation. Full weightbearing with a hinged brace was then allowed 2 weeks after surgery. Various types of athletic training were gradually allowed after 6 weeks, although running was not allowed until 6 months after surgery. Return to full sports activity was generally permitted at 9 months after surgery.

TABLE 1
Patient Demographics

	Substudy 1	Substudy 2
No. of patients	20	20
Age, y, mean (SD)	25.4 (12.5)	27.3 (13.1)
Sex, male:female, n	11:9	9:11
Body height, cm, mean (SD)	165.1 (8.4)	166.0 (8.9)
Body weight, kg, mean (SD)	64.1 (12.2)	63.5 (12.5)

Measurement of the Graft Location

Substudy 1. On the inclined sagittal section image taken with the standard T2-weighted protocol, the whole AM tendon graft was clearly shown as a thick low-intensity band in both the tunnel and the joint space (Figure 3A). In the axial section image, however, it was difficult to clearly distinguish a border between the newly formed fibrous tissue and the grafted tendon. Therefore, only the inclined sagittal section analysis was made in substudy 1. In addition, we analyzed only the AM graft because (1) the AM bundle, which is thicker than the PL graft, exists approximately on the sagittal plane of the knee and is the most essential bundle to be reconstructed in ACL reconstruction, and (2) the AM graft is more acutely bent at the edge of the femoral tunnel outlet than the PL graft. Therefore, in the sagittal plane analysis, we expected that the anterior-shift phenomenon at the edge of the tunnel outlet might be more clearly shown on the AM graft than on the PL graft.

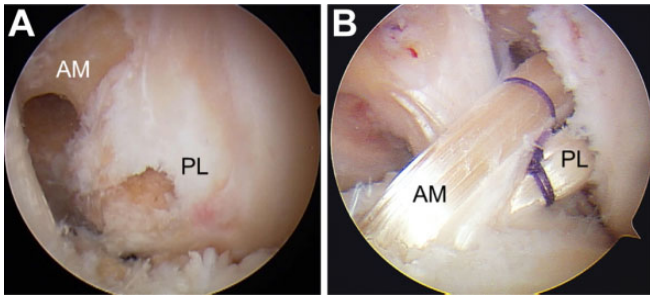


Figure 2. Anatomic double-bundle anterior cruciate ligament (ACL) reconstruction procedure using the transtibial technique. (A) The anteromedial (AM) and posterolateral (PL) tunnels created in the lateral condyle. Note that this arthroscopic photograph was taken from the medial portal at 90° of knee flexion. (B) The 6.5-mm AM and 6.0-mm PL grafts were implanted into the tunnels.

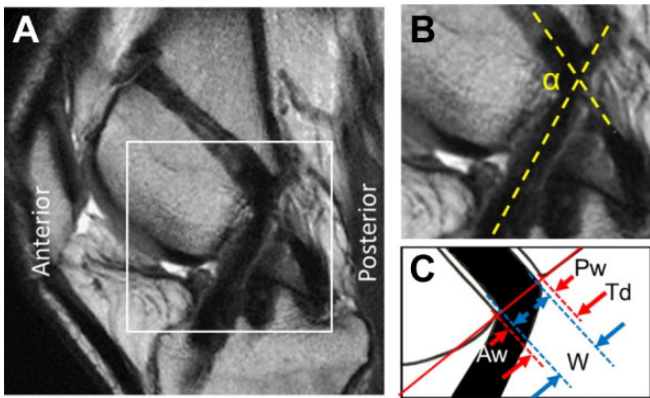


Figure 3. Measurement on the inclined sagittal T2-weighted image (A) of the anteromedial (AM) tendon graft. (A) A thin isointensity zone was found between the low-intensity band and the tunnel wall not only at the posterior part but also in the anterior part. (B) α represents the graft bending angle. (C) A schematic picture of the square shown in (A), and measured parameters. Aw, anterior width; Pw, posterior width; Td, tunnel diameter; W, width of the tendon graft.

On the image of the AM graft, the graft bending angle was measured between the 2 long axes of the intraosseous part and the intra-articular part of the low-intensity band (Figure 3B). A thin isointensity zone was found between the low-intensity band and the tunnel wall not only in the posterior part but also in the anterior part (Figure 3, B and C). To measure the width of each isointensity zone, we drew a reference line on the femoral tunnel outlet and measured the width of the isointensity zones and the low-intensity band using ImageJ software (version 1.48, National Institutes of Health). To show the shift of the tendon graft within the bone tunnel, we marked the center of the tunnel outlet and the center of the low-intensity band on the reference line, and measured the distance between the 2 centers in the same manner. In addition, the femoral tunnel diameter was measured at 3 depth

levels: 0, 5, and 10 mm from the reference line. There was no significant difference in the tunnel diameter among the 3 levels (Table 2). Therefore, the tunnel diameter measured at the tunnel outlet level was used to normalize each measured value.

Substudy 2. On the axial VISTA image taken at the femoral tunnel outlet level, a cross-section of the tendon graft was shown as a round low-intensity zone, and the fibrous tissues that were newly formed between the graft and the tunnel wall³² were shown as a ring-shaped isointensity zone surrounding the tendon graft (Figure 4, A and B). The isointensity was obviously different from the intensity of the joint liquid. To measure the location of the round low-intensity zone in the femoral tunnel, we drew an X-Y coordinate on the cross-section of the tunnel so that the origin corresponded to the center of the tunnel and the Y axis corresponded to the anterior-posterior diameter. Then, we measured the width of the ring-shaped isointensity zone at 4 locations on the X and Y axes (Figure 4B) and defined them as anterior, posterior, medial, and lateral width, respectively, using ImageJ software. To evaluate the degree of the shift of the grafted tendon from the center of the bone tunnel, we marked the center of the low-intensity zone and measured X and Y values of this center on the above-defined X-Y coordinate system (Figure 4C).

Measurement of Tunnel Enlargement

The CT images were measured using a method reported in our previous study.¹¹ The tunnel diameter was measured digitally at 5 mm from the intra-articular outlet of the femoral tunnels in the coronal, sagittal, and axial views, respectively, perpendicular to the direction of the long axis of the tunnels. The percentage change in the diameter between the 2-week and 1-year images was defined as the degree of tunnel enlargement.

Postoperative Clinical Evaluation

The side-to-side anterior laxity was measured using a KT-2000 arthrometer (MEDmetric) at 20° of knee flexion under an anterior drawer force of 133 N. An experienced orthopaedic surgeon performed the pivot-shift test, the results of which were subjectively evaluated as “-,” “+,” and “++,” using the previously reported criteria.¹⁹ For the overall evaluation, the Lysholm knee score (maximum score, 100 points) and the International Knee Documentation Committee (IKDC) form were used.

Second-Look Arthroscopic Examination

During second-look arthroscopy, the AM and PL bundle grafts were observed at various angles of knee flexion by use of the proving technique with both the lateral and medial parapatellar portals. Specifically, the PL bundle was observed in the figure-of-4-position. Evaluation of graft quality was performed using a previously reported grading method,¹⁸ based on the thickness, apparent tension of the graft, and existence of graft laceration.

TABLE 2
Inclined Sagittal Plane Analysis of the Anteromedial Graft Within the Femoral Tunnel
Using Standard T2-Weighted Magnetic Resonance Images

Anteromedial Bundle (n = 20)	Measured Values, Mean (SD)	Normalized Values, %, ^a mean (SD) [95% CI]
Isointensity zone		
Anterior (A) width, mm	0.78 (0.38)	10.5 (5.1) [8.1, 12.9]
Posterior (P) width, mm	0.39 (0.31)	5.2 (4.1) [3.2, 7.2]
A versus P ^b		$t = 3.620$ ($P = .001$); $r = 0.50$; $d = 1.15$
Low-intensity band		
A-P shift, mm ^c	-0.19 (0.37)	-2.5 (4.8) [-4.8, -0.2] ^d
		$t = 2.330$ ($P = .031$); $r = 0.47$; $d = 0.74$
Width, mm	6.40 (0.71)	84.5 (9.3) [80.0, 89.0]
Intraosseous length, ^e mm	16.00 (2.23)	—
Bending angle, ^f deg	74.0 (4.2)	—
Bone tunnel		
Length, mm	45.05 (3.99)	—
Diameter at level 0, ^g mm	7.57 (0.95)	(Used as the reference)
Diameter at level 5, ^g mm	7.46 (0.60)	—
Diameter at level 10, ^g mm	7.51 (0.86)	—

^aThe normalized value was calculated by dividing the measured value by the tunnel diameter.

^bThe anterior width was significantly wider than the posterior width.

^cThe anterior-posterior shift, which was defined as the distance between the center of the low-intensity band and the center of the bone tunnel.

^dThe anterior-posterior shift showed significant posterior (minus value) shift. The effect size was shown with the Spearman correlation coefficient (r) and the standardized mean difference (Cohen d).

^eThe length of the tendon graft located within the femoral tunnel.

^fThe angle between the intraosseous and intra-articular portions of the graft at the tunnel outlet.

^g"Diameter at level 0, 5, or 10" means the diameter measured at the level of 0, 5, or 10 mm proximal to the tunnel outlet level. There were no significant differences between the 3 levels.

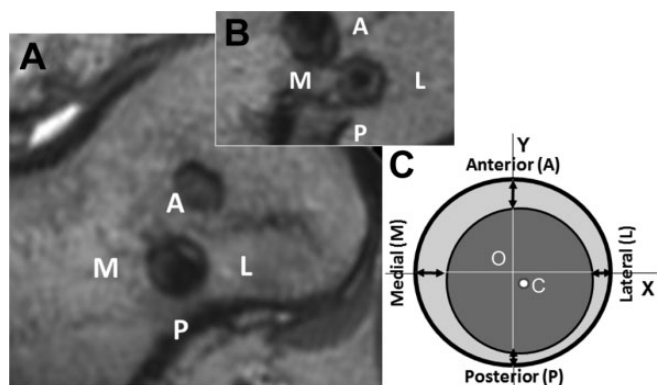


Figure 4. Measurement on the axial VISTA image of the anteromedial (AM) graft (A) and posterolateral (PL) graft (B). (C) An X-Y coordinate was drawn on the cross-section of each tunnel so that the origin (O) corresponded to the center of the tunnel and the Y axis corresponded to the anterior-posterior diameter. Then, the width of the ring-shaped isointensity zone was measured at 4 locations (arrows) on the X and Y axes. The center of the low-intensity zone (the white circle labeled C) was marked, and the X and Y values of this center were measured according to the X-Y coordinate system defined above. VISTA, volume isotropic turbo spin echo acquisition.

Namely, the graft was graded as *excellent* (no laceration or elongation of a sufficiently thick graft), *fair* (superficial laceration of a sufficiently thick graft without

elongation), or *poor* (deep laceration or tear, or obvious elongation of a graft).

Statistical Analysis

In our preliminary study, the intraobserver variability for tunnel measurement was satisfactory (mean intraclass correlation coefficient, 0.93; range, 0.88-0.97). The minimum shift value of the graft center within the tunnel that an observer could detect on the MR image with the naked eye was approximately 5% of the tunnel diameter. To determine the number of participants in each substudy, the statistical power analysis was made using a power analysis program⁵ (G*Power 3; downloaded from <http://www.psych.uni-duesseldorf.de/abteilungen/aap/gpower3/>). The significance level (α) was set at $P = .05$ in each comparison. The power ($1 - \beta$) was set to have 80% or more to test the hypothesis. The expected mean and SD values were obtained from the preliminary study. Data are reported as means and SDs.

To test the hypotheses, Student t test was performed after F test to compare the standard deviation, using a commercially available software program (StatView 5.0, SAS Institute Inc) for statistical calculation. The significance level was set at $P = .05$ in each comparison. We calculated not only t values to determine the statistical significance but also the Cohen d values and the Spearman correlation coefficients (r) to indicate the effect size of the difference.

TABLE 3
Axial Plane Analysis of the AM Graft Within the Femoral Tunnel Using the T2-Weighted VISTA Image^a

AM Bundle (n = 20)	Normalized Value (%), ^b Mean (SD) [95% CI]	Analysis
Isointensity zone		
Anterior width	14.5 (8.3) [10.5, 18.5]	Anterior vs posterior ^c $t = 2.901$ ($P = .006$) $r = 0.56$; $d = 0.92$
Posterior width	6.8 (8.6) [2.7, 10.9]	
Medial width	6.1 (8.1) [2.2, 10.0]	Medial vs lateral ^d $t = 3.331$ ($P = .002$) $r = 0.61$; $d = 1.05$
Lateral width	15.0 (8.8) [10.8, 19.2]	
Low-intensity zone		
Anterior-posterior shift ^e	-3.9 (7.0) [-7.3, -0.5] ^f	$t = 2.490$ ($P = .022$) $r = 0.50$; $d = 0.79$
Anterior-posterior diameter	78.7 (9.6) [74.1, 83.3]	—
Medial-lateral shift	5.5 (6.8) [2.2, 8.8] ^g	$t = 3.575$ ($P = .002$) $r = 0.64$; $d = 1.12$
Medial-lateral diameter	80.9 (9.7) [76.2, 85.6]	—

^aAM, anteromedial; VISTA, volume isotropic turbo spin echo acquisition.

^bThe normalized value was calculated by dividing the measured value by the tunnel diameter.

^cThe t test showed that the anterior width was significantly wider than the posterior width.

^dThe t test showed that the medial width was significantly narrower than the lateral width.

^eThe anterior-posterior shift was defined as the distance between the center of the low-intensity band and the center of the bone tunnel.

^fThe anterior-posterior shift showed significant posterior (minus value) shift.

^gThe medial-lateral shift showed significant medial (minus value) shift. The effect size was shown with the Spearman correlation coefficient (r) and the standardized mean difference (Cohen d).

RESULTS

Sagittal Section Analysis Using the Standard T2 Image (Substudy 1)

On the inclined sagittal section analysis of the AM graft using the standard T2-weighted image (Figure 3), the low-intensity band, the width of which was a mean of 84.5% of the tunnel diameter, was bent at the edge of the tunnel outlet toward the anterior direction by a mean of 74.0° (Table 2). The low-intensity band in the bone tunnel did not directly contact the anterior bony wall of the outlet in each knee, but the isointensity zone, which showed the newly formed fibrous tissue, was observed between the low-intensity band and the anterior wall of the tunnel. The Student t test showed that the width of the anterior isointensity zone (mean, 10.5% of the tunnel diameter) was slightly but significantly greater ($P = .001$) than the width of the posterior isointensity zone (mean, 5.2%) (Table 2). In addition, the center of the low-intensity band was slightly (mean, 2.5%) but significantly ($P = .0310$) shifted from the center of the bone tunnel to the posterior direction (Table 2 and Figure 5).

Axial Section Analysis Using the VISTA Image (Substudy 2)

In both the AM and PL tunnels, a low-intensity zone that showed a cross-section of the tendon graft was surrounded by an isointensity zone that showed the newly formed fibrous tissue (Figure 4). Namely, the low-intensity zone did not directly contact the anterior bony wall in each tunnel.

Concerning the AM tunnel, the anterior width of the isointensity zone (mean, 14.5%) was significantly ($P = .0060$) greater than the posterior width (mean, 6.8%) (Table 3). The center of the low-intensity zone was slightly (mean, 3.9%) but significantly ($P = .022$) shifted from the center of the bone tunnel to the posterior direction. The medial and lateral width of the isointensity zones averaged 4.1% and 15.0% of the tunnel diameter, respectively (Table 3). The medial width was significantly narrower than the lateral width ($P < .0001$). The center of the low-intensity zone was slightly (mean, 5.5%) but significantly ($P = .002$) shifted from the center of the bone tunnel to the medial direction (Table 3 and Figure 5).

Regarding the PL tunnel, the anterior width of the isointensity zone (mean, 9.7%) was not significantly different from the posterior width (mean, 16.8%) (Table 4). Also, there was no significant difference between the proximal and distal width values (Table 4). The center of the low-intensity zone did not show any significant shift from the center of the bone tunnel (Table 4 and Figure 5).

Degree of Tunnel Enlargement

The CT examination showed that in substudy 1, the degree of tunnel enlargement of the femoral AM tunnel were an average (\pm SD) of 8% \pm 12%, 11% \pm 9%, and 6% \pm 10% in the axial, coronal, and sagittal images, respectively, while that of the femoral PL tunnel averaged 9% \pm 11%, 5% \pm 10%, and 7% \pm 10%. In substudy 2, the degree of tunnel enlargement of the femoral AM tunnel averaged 13% \pm 14%, 11% \pm 12%, and 13% \pm 20% in the axial, coronal, and sagittal images, respectively, while that of the femoral PL tunnel averaged 6% \pm 14%, 9% \pm 13%, and 11% \pm 16%. There were no significant differences

TABLE 4
Axial Plane Analysis of the PL Graft Within the Femoral Tunnel Using the T2-Weighted VISTA Image^a

PL Bundle (n = 20)	Normalized Value (%), ^b Mean (SD) [95% CI]	Analysis
Isointensity zone		
Anterior width	9.7 (11.1) [4.4, 15.0]	Anterior vs posterior ^c <i>t</i> = 1.725 (<i>P</i> = .093, NS) <i>r</i> = 0.37; <i>d</i> = 0.55
Posterior width	16.8 (14.7) [9.7, 23.9]	
Medial width	9.1 (9.2) [4.7, 13.5]	Medial vs lateral ^d <i>t</i> = 1.915 (<i>P</i> = .063, NS) <i>r</i> = 0.40; <i>d</i> = 0.63
Lateral width	15.6 (11.3) [10.2, 21.0]	
Low-intensity zone		
Anterior-posterior shift ^e	3.6 (11.2) [-1.8, 9.0] ^e	<i>t</i> = 1.419 (<i>P</i> = .172, NS) <i>r</i> = 0.31; <i>d</i> = 0.32
Anterior-posterior diameter	73.5 (13.4) [67.0, 79.9]	—
Medial-lateral shift ^f	3.3 (9.0) [-1.0, 7.6] ^f	<i>t</i> = 1.618 (<i>P</i> = .122, NS) <i>r</i> = 0.35; <i>d</i> = 0.51
Medial-lateral diameter	75.3 (18.3) [66.5, 84.1]	—

^aNS, not significant; PL, posterolateral; VISTA, volume isotropic turbo spin echo acquisition.

^bThe normalized value was calculated by dividing the measured value by the tunnel diameter.

^cThe *t* test showed that there was no significant difference between the anterior width and the posterior width.

^dThe *t* test showed that there was no significant difference between the medial width and the lateral width.

^eThe anterior-posterior shift showed no significant shift from the tunnel center.

^fThe medial-lateral shift showed no significant shift from the tunnel center. The effect size was shown with the Spearman correlation coefficient (*r*) and the standardized mean difference (Cohen *d*).

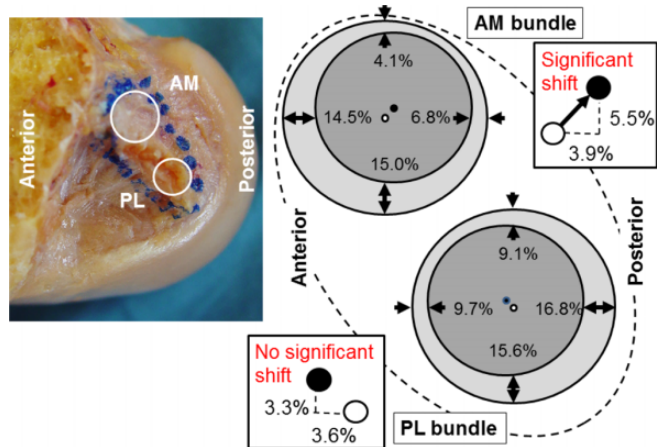


Figure 5. A summary of the analyses performed with the VISTA images. The anteromedial (AM) graft or posterolateral (PL) graft did not attach to the anterior wall of the tunnel. The AM graft was slightly but significantly shifted posteriorly and proximally in the tunnel. The PL graft in the tunnel was not significantly shifted from the center of the tunnel located approximately at the center of the tunnel. VISTA, volume isotropic turbo spin echo acquisition.

between the 2 subgroups. In each subgroup, there were no knees with a tunnel enlarged by 30% or more.

Postoperative Clinical Evaluation

In each substudy, the clinical results of the 20 patients were favorable, as shown in Table 5. The anterior laxity averaged

0.8 ± 0.9 mm for patients in substudy 1 and 0.9 ± 0.9 for those in substudy 2. There was no significant difference in any parameter between the 2 substudy groups (Table 5).

Arthroscopic Evaluation

In substudy 1, the AM and PL bundles were graded as excellent in 18 knees (90%) and 17 knees (85%), respectively, and graded as fair in 2 knees (10%) and 3 knees (15%), respectively. There were no knees in which the AM or PL bundle was evaluated as poor. In substudy 2, the AM and PL bundles were graded as excellent in 19 knees (95%) and 18 knees (90%), respectively, and graded as fair in 1 knee (5%) and 2 knees (10%), respectively. There were no bundles evaluated as poor.

DISCUSSION

The present study demonstrated the following results: First, on the inclined sagittal T2-weighted image, the anterior width of the isointensity zone (mean, 10.5%) was slightly but significantly greater than the posterior width (mean, 5.2%). In addition, the center of the low-intensity band was slightly (mean, 2.5%) but significantly shifted posteriorly from the center of the bone tunnel. Second, on the axial VISTA image of the AM bundle, the anterior width of the isointensity zone (mean, 14.5%) was significantly greater than the posterior width (mean, 6.8%). In addition, the center of the low-intensity zone was slightly but significantly shifted posteriorly and proximally (mean, 3.9% and 5.5%, respectively) from the center of the bone tunnel (Figure 5). Third, on the axial VISTA image of the

TABLE 5
Subjective and Functional Results^a

	Substudy 1 (n = 20)	Substudy 2 (n = 20)	Comparison
Loss of extension (>5°)	1 patient	0 patients	NS
Loss of flexion (>15°)	0 patients	0 patients	NS
Lysholm knee score, points, mean (SD)	97.2 (5.7)	96.8 (4.9)	NS
IKDC evaluation, patients, n (%)			NS
A (normal)	17 (85)	18 (90)	
B (nearly normal)	2 (10)	1 (5)	
C (nearly abnormal)	1 (5)	1 (5)	
D (abnormal)	0 (0)	0 (0)	
Anterior laxity, mm, mean (SD)	0.8 (0.9)	0.9 (1.0)	NS
Pivot-shift test (knees), n (%)			
(−)	17 (85)	18 (90)	NS
(+)	3 (15)	2 (10)	
(++)	0 (0)	0 (0)	

^aIKDC, International Knee Documentation Committee; NS, not significant.

PL bundle, the anterior width of the isointensity zone (the mean, 9.7%) was not significantly different from the posterior width (mean, 16.8%), and the center of the low-intensity zone did not show any significant shift from the center of the bone tunnel in any direction (Figure 5).

These findings showed that, first, the grafted tendon was not shifted anteriorly in each femoral tunnel at the 1-year period after anatomic double-bundle ACL reconstruction. Second, the PL graft was located approximately at the center of the tunnel, while the AM graft was slightly but significantly shifted posteriorly and proximally. In each tunnel, the grafted tendon was fixed with the fibrous tissue. The results suggest that the clinical significance of the anterior-shift phenomenon observed immediately after surgery should be corrected. In addition, this new information on the graft location in the tunnel will influence the debate on tunnel creation procedures for anatomic double-bundle reconstruction.

The CT examination showed that there were no knees with coalition of the femoral tunnel outlets at each period. Commonly, tunnel coalition occurs due to an intraoperative technical error in which the 2 tunnel outlets are created too close together. However, our previous study demonstrated that our procedure could successfully prevent femoral tunnel outlet coalition at the time of surgery.¹⁵ Therefore, we can say that the graft-shift phenomenon observed in the present result was not affected by tunnel coalition or the crossover effect of drilling a second femoral tunnel. In addition, the fact that each femoral tunnel was independently created implied that the present study results concerning the AM tunnel are applicable to conventional single-bundle ACL reconstruction procedures, because the aim of these procedures is to anatomically reconstruct the AM bundle. In addition, the CT examination showed that the maximal degree of femoral AM and PL tunnel enlargement was an average of 13% and 11%, respectively. According to the published literature, the degree of the femoral tunnel enlargement after single-bundle reconstruction procedures using the hamstring graft is 33% to 63%.^{2,4,10,11,27,28} The degree of femoral tunnel enlargement measured in the

present study appears to be lower in comparison with the previously reported data after single- and double-bundle reconstruction. Therefore, we consider that the center-shift phenomenon observed in the present study was not an unusual phenomenon observed only in an extremely enlarged tunnel, but a phenomenon observed in a common femoral tunnel. The reason why the degree of the femoral tunnel enlargement was lower in comparison with the previous studies may be that the femoral tunnel coalition was rare in our procedure and that the compression forces from the graft to the tunnel outlet edge could be reduced by distributing the total force to the 2 tunnels.¹⁵

The present study suggests that the graft location in the femoral tunnel moved from the anterior edge in the tunnel to nearly the central portion of the tunnel during the graft remodeling period. Concerning the mechanism of the location change of the grafted tendon, the present study indicates that the change of the graft location was not caused by loss of graft tension due to intra-articular graft failure or elongation. Namely, the postoperative anterior laxity averaged 0.8 ± 0.9 mm in substudy 1 and 0.9 ± 0.9 mm in substudy 2, and the arthroscopic observation showed that there were no knees with deep laceration or obvious elongation of a graft. These results show that the reconstructed ACLs functioned adequately. Therefore, we should consider that the posterior-shift phenomenon of the grafted tendon must be biologically induced in the remodeling phase of the functioning graft after surgery.

A part of the biological mechanism of the posterior-shift phenomenon may be explained by previous basic studies using a canine ACL reconstruction model. Tomita et al³² showed that the tendon graft was located approximately at the center of the tunnel even at 3 weeks after ACL reconstruction, even though the graft was bent at the edge of the tunnel outlet. Yamazaki et al³⁵ indicated that, even in ACL reconstruction with large graft-tunnel diameter disparity (a 4-mm graft grafted in a 6-mm tunnel), the graft was anchored to the bony wall with the newly formed fibrous tissues approximately at the center of the tunnel at 3 and 6 weeks. These basic studies showed that, regardless of the

degree of the graft-tunnel diameter disparity, the whole space between the tendon and the bony wall was filled with granulation tissue at 3 weeks, in which perpendicular collagen fibers resembling Sharpey fibers connected the tendon to the bony wall. Interestingly, these collagen fibers were rarely found in the gap where compression stresses were applied to the tunnel wall by the tendon, but found in the opposite gap where tensile stresses were applied. In addition, a cartilage-like tissue was generated at 12 weeks in the gap near the tunnel outlet, where compression stresses were applied. It is considered that the generation of the Sharpey-like fibers as well as the cartilage-like tissues may be controlled by Wolf's law and that these tissues anchored the grafted tendon approximately at the center of the bone tunnel. In the present study, the fibrous tissue around the grafted tendon was enhanced in the VISTA image. Based on the experimental study results, we can speculate that, in the femoral tunnel after human ACL reconstruction, the Sharpey-like fibers generated in the posterior gap, where tensile stresses were applied, might pull the tendon graft posteriorly. In addition, the cartilage-like tissue might generate in the anterior edge of the tunnel outlet, where compression stresses were applied, and push the tendon graft posteriorly. Subsequently, the graft was tightly anchored to the tunnel wall at almost the center of the bone tunnel. However, it is difficult to histologically verify this speculation in clinical studies. Therefore, further experimental studies with large animals are needed in the near future to verify this speculation.

In the present MRI study, we used standard T2-weighted images and the 3D VISTA images. In previous studies using MRI, the quality and quantity of the tendon graft has been commonly evaluated with the standard T2-weighted protocol.^{6,22} However, it was difficult in the standard T2 image to precisely analyze the intraosseous tendon location on the axial view, which was the most essential for analyzing the graft location. This may be a reason why the grafted tendon location in the tunnel at the postremodeling phase has not been reported previously. Therefore, we used the recently developed 3D VISTA image.^{13,30,40} The VISTA image could clearly show the location of the tendon graft in the bone tunnel by differentiating the grafted tendon tissue and the newly generated fibrous tissue. Recently, the VISTA imaging with multiplanar reconstruction has attracted notice to analyze the quality of the ligament and tendon tissues, because the diagnostic performance of the reformatted VISTA image was comparable or superior to that of a conventional 2D FSE image (see Appendix 1). Yi et al⁴⁰ reported that the contrast-to-noise ratio between the soft tissue and the fluid on the 3D VISTA image was significantly higher than on a 2D FSE image. In a few studies, therefore, the VISTA image was successfully used to diagnose ACL injuries. Therefore, we believe that the data measured on the VISTA images in the present study are reliable. Based on the present study and the previous literature, the reformatted 3D VISTA image may be able to replace the conventional 2D oblique image in the evaluation of ACL graft complications.

There are some limitations in the present study. First, the present study was not a randomized study, although

we enrolled consecutive patients who underwent anatomic ACL reconstruction in our hospital during the selected period. Therefore, we can not completely deny the issue that there might exist some selection bias. Second, we did not examine each patient using the 2 different MRI protocols, because it would impose a great burden on the patients. Therefore, we cannot say that the 2 subgroups were identical, although there were no significant differences in the demographics and the clinical results between the 2 substudies. Third, we did not examine each patient with an MRI twice, at the early phase and then at the postremodeling phase after surgery. Therefore, we can not clarify when the graft location changed from the anterior edge of the tunnel to the tunnel center. Fourth, concerning the measurement of the length, although we evaluated intraobserver variability in the present study, we did not evaluate other variabilities. Fifth, we did not analyze the graft location in the tibial tunnels. This issue may be the focus in a future study. Although the present study has these limitations, we believe that this study adds important new information on intraosseous graft healing to the clinical field concerning ACL reconstruction.

As for clinical relevance, the current study adds information to the debate concerning femoral tunnel creation in anatomic double-bundle ACL reconstruction. Recently, Fujii et al⁷ conducted an *in vitro* simulation study to measure the amount of the tendon graft shift placed in a 7-mm tunnel created in a metal block and reported that the maximum graft shift averaged 1.10 mm at a graft bending angle of 75°. Therefore, some surgeons have recommended that each femoral tunnel be created at a point more posteriorly to the center of the AM or PL attachment, taking the anterior-shift phenomenon into account.^{7,17} However, the present study has shown that the PL graft was located approximately at the center of the tunnel outlet at the 1-year period after ACL reconstruction, and the AM graft was slightly shifted posteriorly and proximally (mean, 3.9% and 5.5%, respectively) from the center (Figure 5). These findings suggest that the anterior-shift phenomenon observed just after surgery is not necessary for a surgeon to take into account when deciding a guide wire location for femoral tunnel creation during ACL reconstruction. Thus, the present study supported the original recommendation that surgeons should create each femoral tunnel at the center of the AM and PL bundle attachments, respectively, in anatomic double-bundle ACL reconstruction,^{34,37} because biomechanical studies have shown that the 2 grafts implanted into such tunnels have nearly normal functions of the AM and PL bundles, respectively.^{20,34,36,39} Recently, 2 CT studies observed that the femoral tunnels enlarged in a certain direction by approximately 1 mm after double-bundle ACL reconstruction.^{1,31} However, no consensus has been made concerning this type of tunnel enlargement because the direction of the tunnel enlargement was different between the 2 studies. In addition, the degree and incidence of such enlargement phenomena have been unknown. Therefore, the present study cannot refer to this phenomenon.

CONCLUSION

The grafted tendon was not shifted anteriorly in each femoral tunnel at the 1-year period after anatomic double-bundle ACL reconstruction. The grafted tendons were surrounded by newly formed fibrous tissue in each tunnel. The PL graft was located approximately at the center of the tunnel, while the AM graft was slightly but significantly shifted posteriorly and proximally. These facts suggest that the anterior-shift phenomenon observed just after surgery is not necessary for a surgeon to take into account when deciding a guide wire location for femoral tunnel creation during the ACL reconstruction. Namely, surgeons should create each femoral tunnel at the center of the AM and PL bundle attachments, respectively, in anatomic double-bundle ACL reconstruction.

REFERENCES

- Araki D, Kuroda R, Matsumoto T, et al. Three-dimensional analysis of bone tunnel changes after anatomic double-bundle anterior cruciate ligament reconstruction using multidetector-row computed tomography. *Am J Sports Med.* 2014;42:2234-2241.
- Buelow JU, Siebold R, Ellermann A. A prospective evaluation of tunnel enlargement in anterior cruciate ligament reconstruction with hamstrings: extracortical versus anatomical fixation. *Knee Surg Sports Traumatol Arthrosc.* 2002;10:80-85.
- Busse RF, Brau ACS, Vu A, et al. Effects of refocusing flip angle modulation and view ordering in 3D fast spin echo. *Magn Reson Med.* 2008;60:640-649.
- Clatworthy MG, Annear P, Bulow JU, Bartlett RJ. Tunnel widening in anterior cruciate ligament reconstruction: a prospective evaluation of hamstring and patella tendon grafts. *Knee Surg Sports Traumatol Arthrosc.* 1999;7:138-145.
- Faul F, Erdfelder E, Lang AG, Buchner A. G*Power 3: a flexible statistical power analysis program for the social, behavioral, and biomedical sciences. *Behav Res Methods.* 2007;39:175-191.
- Fleming BC, Vajapeyam S, Connolly SA, Magarian EM, Murray MM. The use of magnetic resonance imaging to predict ACL graft structural properties. *J Biomech.* 2011;44:2843-2846.
- Fujii M, Sasaki Y, Araki D, et al. Evaluation of the semitendinosus tendon graft shift in the bone tunnel: an experimental study. *Knee Surg Sports Traumatol Arthrosc.* 2016;24:2773-2777.
- Fushimi Y, Miki Y, Kikuta K, et al. Comparison of 3.0- and 1.5-T three-dimensional time-of-flight MR angiography in moyamoya disease: preliminary experience. *Radiology.* 2006;239:232-237.
- Gold GE, Busse RF, Beehler C, et al. Isotropic MRI of the knee with 3D fast spin-echo extended echo-train acquisition (XETA): initial experience. *AJR Am J Roentgenol.* 2007;188:1287-1293.
- Jansson KA, Harilainen A, Sandelin J, Karjalainen PT, Aronen HJ, Tallroth K. Bone tunnel enlargement after anterior cruciate ligament reconstruction with the hamstring autograft and endobutton fixation technique. A clinical, radiographic and magnetic resonance imaging study with 2 years follow-up. *Knee Surg Sports Traumatol Arthrosc.* 1999;7:290-295.
- Jarvela T, Moisala AS, Paakkala T, Paakkala A. Tunnel enlargement after double-bundle anterior cruciate ligament reconstruction: a prospective, randomized study. *Arthroscopy.* 2008;24:1349-1357.
- Jung JY, Yoon YC, Kwon JW, Ahn JH, Choe BK. Diagnosis of internal derangement of the knee at 3.0-T MR imaging: 3D isotropic intermediate-weighted versus 2D sequences. *Radiology.* 2009;253:780-787.
- Jung JY, Jee WH, Park MY, Lee SY, Kim YS. Supraspinatus tendon tears at 3.0 T shoulder MR arthrography: diagnosis with 3D isotropic turbo spine-echo SPACE sequence versus 2D conventional sequences. *Skeletal Radiol.* 2012;41:1401-1410.
- Kai S, Kondo E, Kitamura N, et al. A quantitative technique to create a femoral tunnel at the averaged center of the anteromedial bundle attachment in anatomic double-bundle anterior cruciate ligament reconstruction. *BMC Musculoskelet Disord.* 2013;14:189.
- Kawaguchi Y, Kondo E, Onodera J, et al. Tunnel enlargement and coalition after anatomic double-bundle anterior cruciate ligament reconstruction with hamstring tendon autografts: a computed tomography study. *Orthop J Sports Med.* 2013;1:2325967113486441.
- Kijowski R, Davis KW, Woods MA, et al. Knee joint: comprehensive assessment with 3D isotropic resolution fast spin-echo MR imaging—diagnostic performance compared with that of conventional MR imaging at 3.0 T. *Radiology.* 2009;252:486-495.
- Koga H, Muneta T, Yagishita K, et al. Evaluation of a behind-remnant approach for femoral tunnel creation in remnant-preserving double-bundle anterior cruciate ligament reconstruction. Comparison with a standard approach. *Knee.* 2015;22:249-255.
- Kondo E, Yasuda K. Second-look arthroscopic evaluations of anatomic double-bundle anterior cruciate ligament reconstruction: relation with postoperative knee stability. *Arthroscopy.* 2007;23:1198-1209.
- Kondo E, Yasuda K, Azuma H, Tanabe Y, Yagi T. Prospective clinical comparisons of anatomic double-bundle versus single-bundle anterior cruciate ligament reconstruction procedures in 328 consecutive patients. *Am J Sports Med.* 2008;36:1675-1687.
- Kondo E, Merican AM, Yasuda K, Amis AA. Biomechanical comparisons of knee stability after anterior cruciate ligament reconstruction between 2 clinically available transtibial procedures: anatomic double-bundle versus single bundle. *Am J Sports Med.* 2010;38:1349-1358.
- Kwon JW, Yoon YC, Choi SH. Three-dimensional isotropic T2-weighted cervical MRI at 3 T: comparison with two-dimensional T2-weighted sequences. *Clin Radiol.* 2012;67:106-113.
- Murakami Y, Sumen Y, Ochi M, Fujimoto E, Deie M, Ikuta Y. Appearance of anterior cruciate ligament autografts in their tibial bone tunnels on oblique axial MRI. *Magn Reson Imaging.* 1999;17:679-687.
- Natsu-ume T, Shino K, Nakata K, Nakamura N, Toritsuka Y, Mae T. Endoscopic reconstruction of the anterior cruciate ligament with quadrupled hamstring tendons. A correlation between MRI changes and restored stability of the knee. *J Bone Joint Surg Br.* 2001;83:834-837.
- Okuma H, Gonoji W, Ishida M, et al. Comparison of attenuation of striated muscle between postmortem and antemortem computed tomography: results of a longitudinal study. *PLoS One.* 2014;9:e111457.
- Ristow O, Steinbach L, Sabo G, et al. Isotropic 3D fast spin-echo imaging versus standard 2D imaging at 3.0 T of the knee—image quality and diagnostic performance. *Eur Radiol.* 2009;19:1263-1272.
- Segawa H, Koga Y, Omori G, Sakamoto M, Hara T. Influence of the femoral tunnel location and angle on the contact pressure in the femoral tunnel in anterior cruciate ligament reconstruction. *Am J Sports Med.* 2003;31:444-448.
- Siebold R, Kiss ZS, Morris HG. Effect of compaction drilling during ACL reconstruction with hamstring on postoperative tunnel widening. *Arch Orthop Trauma Surg.* 2008;128:461-468.
- Siebold R, Cafaltzis K. Differentiation between intraoperative and postoperative bone tunnel widening and communication in double-bundle anterior cruciate ligament reconstruction: a prospective study. *Arthroscopy.* 2010;26:1066-1073.
- Stevens KJ, Busse RF, Han E, et al. Ankle: isotropic MR imaging with 3D-FSE-cube—initial experience in healthy volunteers. *Radiology.* 2008;249:1026-1033.
- Subhas N, Kao A, Freire M, Polster JM, Obuchowski NA, Winalski CS. MRI of the knee ligaments and menisci: comparison of isotropic-resolution 3D and conventional 2D fast spin-echo sequences at 3 T. *AJR Am J Roentgenol.* 2011;197:442-450.
- Tachibana Y, Mae T, Shino K, et al. Morphological changes in femoral tunnels after anatomic anterior cruciate ligament reconstruction. *Knee Surg Sports Traumatol Arthrosc.* 2015;23:3591-3600.
- Tomita F, Yasuda K, Mikami S, Sakai T, Yamazaki S, Tohyama H. Comparisons of intraosseous graft healing between the doubled

- flexor tendon graft and the bone–patellar tendon–bone graft in anterior cruciate ligament reconstruction. *Arthroscopy*. 2001;17:461-476.
33. Tsuda E, Fukuda Y, Loh JC, Debski RE, Fu FH, Woo SL. The effect of soft-tissue graft fixation in anterior cruciate ligament reconstruction on graft-tunnel motion under anterior tibial loading. *Arthroscopy*. 2002;18:960-967.
 34. Yagi M, Wong EK, Kanamori A, Debski RE, Fu FH, Woo SL. Biomechanical analysis of an anatomic anterior cruciate ligament reconstruction. *Am J Sports Med*. 2002;30:660-666.
 35. Yamazaki S, Yasuda K, Tomita F, Minami A, Tohyama H. The effect of graft-tunnel diameter disparity on intraosseous healing of the flexor tendon graft in anterior cruciate ligament reconstruction. *Am J Sports Med*. 2002;30:498-505.
 36. Yasuda K, Ichiyama H, Kondo E, Miyatake S, Inoue M, Tanabe Y. An in vivo biomechanical study on the tension-versus-knee flexion angle curves of 2 grafts in anatomic double-bundle anterior cruciate ligament reconstruction: effects of initial tension and internal tibial rotation. *Arthroscopy*. 2008;24:276-284.
 37. Yasuda K, Kondo E, Ichiyama H, et al. Anatomic reconstruction of the anteromedial and posterolateral bundles of the anterior cruciate ligament using hamstring tendon grafts. *Arthroscopy*. 2004;20:1015-1025.
 38. Yasuda K, Kondo E, Ichiyama H, Tanabe Y, Tohyama H. Clinical evaluation of anatomic double-bundle anterior cruciate ligament reconstruction procedure using hamstring tendon grafts: comparisons among 3 different procedures. *Arthroscopy*. 2006;22:240-251.
 39. Yasuda K, Tanabe Y, Kondo E, Kitamura N, Tohyama H. Anatomic double-bundle anterior cruciate ligament reconstruction. *Arthroscopy*. 2010;26(suppl):S21-S34.
 40. Yi JW, Park HJ, Lee SY, et al. Usefulness of the oblique view of three-dimensional isotropic T2-weighted fast spin-echo (VISTA) in the evaluation of anterior cruciate ligament reconstruction. *Clin Imaging*. 2016;40:610-616.

APPENDIX 1

MRI Protocols

In substudy 1, the knee joint was centered in an 8-channel knee coil in the supine position with the knee slightly flexed, and the standard T2-weighted images were acquired using the following parameters: slice thickness, 3 mm; slice gap, 0.3 mm; repetition time (TR), 4000 to 4500 ms; TE, 70 ms; FA, 90°; matrix size, 384 × 313; number of slices, 23; and acquisition time, 3 minutes 11 seconds.

In substudy 2, the knee joint of each patient was centered in an 8-channel knee coil in the supine position with the knee slightly flexed, and the 3D VISTA images were taken using the following parameters: TR, 3000 ms; TE, 139 ms; turbo spin echo (TSE) factor, 84; matrix size, 120 × 120; slice thickness, 1 mm; number of slices, 150; and acquisition time, 4 minutes 33 seconds. Previously, quality of 3D reformatted MRI images was too poor to evaluate the tendon and ligament tissues. However, these problems have recently been solved by applying a very long echo train with variable refocusing flip angle modulation. Namely, the 3D VISTA protocol was developed to acquire thin-section data without an interslice gap.^{3,16,29} The 3D VISTA imaging with multiplanar reconstruction has recently attracted notice to analyze various musculoskeletal tissues due to a short acquisition time and the comparable image quality to

the 2D FSE sequence imaging. The diagnostic performance of the reformatted VISTA image for injuries of the knee joint structures was comparable or superior to that of conventional 2D FSE image,^{9,21,25} and the contrast-to-noise ratio between the soft tissue and the fluid on the 3D VISTA image was significantly higher than on a 2D FSE image.⁴⁰ In addition, several studies described that the accuracy of the 3D VISTA image was comparable to that of a 2D FSE image in diagnosis of ACL injuries,^{12,21} and that this image was helpful for the analysis of the tendon and ligament structures.^{12,30,40}

APPENDIX 2

Current Information on zioTerm2009

The 3D DICOM Viewer software, zioTerm2009 (Ziosoft Inc), could be downloaded from the website, <https://www.zio.co.jp/products/zioTerm2009/>. Because zioTerm2009 can display high-definition volume-rendered images on a monitor, this software has been successfully used in various scientific researches.^{8,24,40} Currently, however, zioTerm2009 cannot be downloaded, and all service on this software will be closed on May 31, 2017. The reason is that zioTerm2009 has progressed to a new software, Ziocube (Ziosoft Inc), which is commercially available instead of zioTerm2009.