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Comparison of graft bending angle during knee motion after outside-in, trans-portal and trans-tibial anterior cruciate ligament reconstruction

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Abstract

Purpose To determine graft bending angle (GBA) during knee motion after anatomic anterior cruciate ligament (ACL) reconstruction and to clarify whether surgical techniques affect GBA. Our hypotheses were that the graft bending angle would be highest at knee extension and the difference of surgical techniques would affect the bending steepness.

Methods Eight healthy volunteers with a mean age of 29.3 ± 3.0 years were recruited and 3D MRI knee models were created at three flexion angles (0°, 90° and 130°). Surgical simulation of the tunnel drilling was performed with anatomic tunnel position using each outside-in (OI), trans-portal (TP) and trans-tibial (TT) techniques on the identical cases. The models were matched to other knee positions and the GBA in 3D was measured using computational software. Double-bundle ACL reconstruction was analysed first, and single-bundle reconstruction was also analysed to evaluate its effect to reduce GBA. A repeated-measures ANOVA was used to compare GBA difference at three flexion angles, by three techniques or of three bundles.

Results GBA changed substantially with knee motion, and it was highest at full extension ($p < 0.001$) in each surgical technique. OI technique exhibited highest GBA for anteromedial bundle (94.3° ± 5.2°) at extension, followed by TP (83.1° ± 6.5°) and TT (70.0° ± 5.2°) techniques ($p < 0.01$). GBA for posterolateral bundle at extension were also high in OI (84.6° ± 7.4°), TP (83.0° ± 6.3°) and TT (77.2° ± 7.0°) techniques (n.s.). Single-bundle grafts did not decrease GBA compared with double-bundle grafts. In OI technique, a more proximal location of the femoral exit reduced GBA of each bundle at extension and 90° flexion.

Conclusion A significant GBA change with knee motion and considerably steep bending at full extension, especially with OI and TP techniques, were simulated. Although single-bundle technique did not reduce GBA as seen in double-bundle technique, proximal location of femoral exits by OI technique, with tunnels kept in anatomic position, was effective in decreasing GBA at knee extension and flexion. For clinical relevance, high stress on graft and bone interface has been suggested by steep GBA at full extension after anatomic ACL reconstruction.

Level of evidence Therapeutic study (prospective comparative study), Level II.

Keywords Anterior cruciate ligament reconstruction · Graft bending angle · Computer simulation · Graft stress · Anatomic

Abbreviations

GBA	Graft bending angle
ACL	Anterior cruciate ligament
OI	Outside-in
TP	Trans-portal
TT	Trans-tibial
AM	Anteromedial
PL	Posterolateral
MRI	Magnetic resonance imaging
ICC	Intraclass/interclass correlation coefficients

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Introduction

In order to restore normal knee kinematics after anterior cruciate ligament (ACL) injury, anatomic ACL reconstruction has been advocated in recent years [45, 55]. Because malposition of bone tunnels could lead to inferior clinical outcomes [7, 27, 56, 60], placement of the graft within anatomic footprint is very important. Outside-in (OI) and trans-portal (TP) techniques make it possible to create femoral tunnels independently from tibial tunnels [8, 20, 29, 45] and are more advantageous in locating femoral tunnels anatomically, compared with traditional trans-tibial (TT) technique [9, 25, 49, 51, 54]. Reconstruction of the main two bundles of ACL fibres, anteromedial (AM) and posterolateral (PL) bundles, efficiently reproduces the direction of fibres and covers the native ACL footprint [41, 48, 53]. In terms of biomechanics, anatomic double-bundle ACL reconstruction is useful in stabilizing knee instability after ACL injury, especially in specific cases of substantial rotatory instability and large insertion sites [6, 11, 45].

However, in certain cases after ACL reconstruction, partial damage or poor synovial coverage on the reconstructed graft are found during second-look arthroscopy and relating laxity has been also reported [1, 24, 33, 39]. Possible causes of them include impingement against intercondylar wall [17, 19], higher forces or tension in PL graft near extension [31], greater graft length change during knee motion and increased length at extension in anatomic ACL reconstruction [28], acute graft bending angles and windshield wiper and bungee cord effect [10, 26]. With regard to these factors, higher forces or tension and great length change near extension may be functions of the normal ACL [2, 3, 43], and graft impingement has been reported to be unlikely in anatomic ACL reconstruction [15, 16], whereas the graft bending angle (GBA) which is determined by the angle between the bone tunnel and the graft is recently drawing back the attention as a cause of stress between the bone and the reconstructed graft [22, 36, 40, 46]. The repetitive bending and the abrasive force at the sharp femoral aperture due to the high GBA may cause excessive stress on the graft and this can be a possible cause of graft damage or poor synovial coverage after ACL reconstruction [35, 36, 44]. Graft deformation at the corner of the femoral tunnel aperture has also been reported after anatomic ACL reconstruction [37]. Furthermore, the graft bending angles might be steeper in some anatomic ACL reconstruction techniques [23, 50, 57].

The purpose of this study was to determine graft bending angle (GBA) changes during knee motion after anatomic ACL reconstruction with outside-in (OI), trans-portal (TP) and trans-tibial (TT) techniques, and to clarify whether GBA was affected by surgical techniques. Our hypotheses were that (1) the GBA would change during the knee motion and steep bending could occur at full extension after anatomic ACL reconstruction and (2) the bending steepness would be affected by surgical techniques.

Materials and methods

Eight healthy volunteers (4 males and 4 females) with eight normal knees were recruited. The median age was 29.5 years (range 24–32 years). They had no history of ACL, meniscal or any other knee injury. A horizontal open magnetic resonance imaging (MRI) (Aperto®, Hitachi Medical Co, Tokyo, Japan) was applied to enable the knee flexion at the gantry and T2-weighted MRI images (TR/TE = 2800/100 ms, field of volume = 150 mm, thickness = 1.0 mm) were scanned at 0°, 90° and 130° knee flexion. A goniometer with the non-magnetic material was used to ensure the desired flexion angles. 3D knee models were created from the series of 1-mm slices two-dimensional contours using the 3D reconstruction algorithm on the 3D processing software programme, Mimics® (Materialise, Leuven, Belgium).

Simulation of femoral tunnel drilling in ACL reconstruction

Surgical simulation of the bone tunnel drilling procedure within anatomic footprint was performed using each of outside-in (OI) [8, 20, 30, 32], trans-portal (TP) [12, 25, 29, 34, 45] and trans-tibial (TT) [14, 58, 59] techniques separately on the same knee model (Fig. 1a–c). Knee flexion angles and tunnel positions during the drilling were made almost the same with the actual ACL reconstruction in order to make the simulation as close as possible to the real surgery. First, double-bundle ACL reconstructions were simulated. And then, single-bundle reconstructions with centre-to-centre tunnel position [13] were also simulated to evaluate its effect to reduce the graft bending steepness.

For the simulation of the OI technique, 90° knee flexion models were used. Femoral and tibial tunnel centres were located anatomically with use of the insertion site in multiplanar reconstruction (MPR) MRI images. The locations were verified in 3D knee models, in which both the AM and PL tunnel apertures were located posterior to the resident's ridge [5, 18, 42], and were within the anatomic footprint. As a standard OI technique, femoral exit of the PL-bundle graft was determined just anterior-proximal to the lateral epicondyle in order to avoid damaging the proximal insertion of lateral collateral ligament, and the exit of the AM-bundle was located 1 cm anterior-proximal of the PL-bundle exit. Then, an alternative OI technique was also simulated with each of the femoral exits located 1 cm proximally from the standard OI exits. The intraarticular tunnel

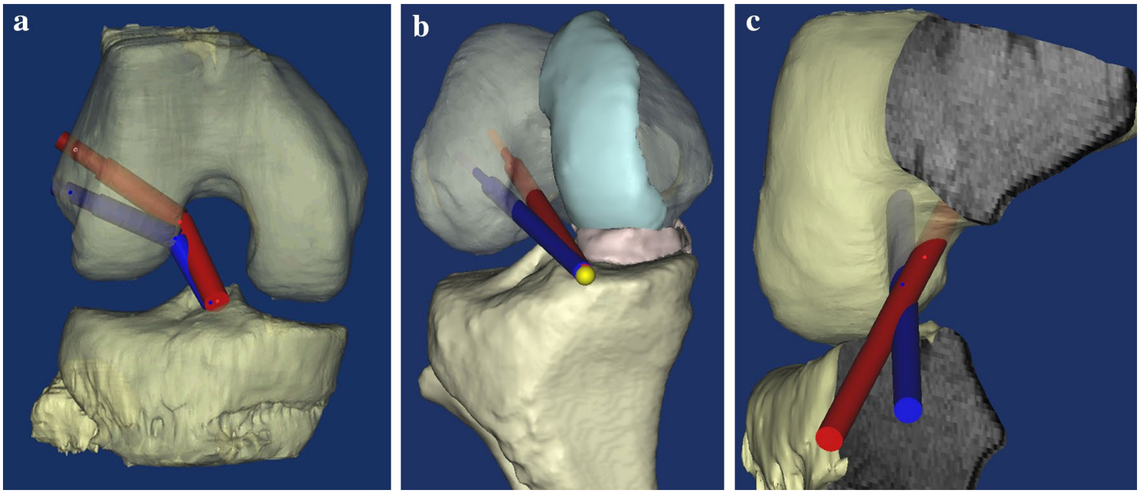

Fig. 1 Simulation of femoral tunnel drilling in double-bundle ACL reconstruction is shown. **a** In outside-in (OI) technique, 90° knee flexion model was used. Femoral and tibial apertures were located in anatomic antero-medial (AM) and postero-lateral (PL) footprint. Femoral exits were located just anterior-proximal to the lateral epicondyle in standard OI simulation. **b** In trans-portal (TP) technique, 130° flexion model was used. Virtual drill cylinders to connect accessory far medial portal (*yellow*) and anatomic AM and PL footprints were made and extended to femoral cortex. **c** In trans-tibial (TT) technique, femoral AM tunnel aperture centre was slightly shifted to anterior-distal position within ACL footprint, so as to avoid posterior blowout. Tibial footprints and femoral aperture centres were connected for each AM and PL bundles and extended to femoral cortex

apertures in the alternative OI technique were kept in the same anatomic position.

In the TP technique, 130° knee flexion models were used. Femoral and tibial tunnel centres were located on the anatomic position in the same manner as OI technique. The accessory medial portal was determined just above the anterior horn of the medial meniscus and about 2 cm medial to the patellar tendon edge, so that the drill with 6 mm diameter would not damage the articular cartilage of the medial femoral condyle. The virtual drills to connect the accessory medial portal and the femoral tunnel apertures in each AM-bundle and PL-bundle were extended to the lateral femoral cortex and the exit points were determined.

In the TT technique, 90° knee flexion models were used. In order to avoid posterior wall blow out of the femur by connecting anatomic footprints from tibia to femur, the femoral AM tunnel centre was shifted slightly distal and anterior within the footprint. If necessary, varus tilting and internal rotation of the tibia up to 5° were added according to the modified trans-tibial technique [59]. As a result, all of the AM tunnels in TT technique were located within the native ACL footprint. Femoral and tibial tunnel positions for AM, PL and single bundle in each surgical technique are shown in Table 1, according to the quadrant method [4, 52].

Evaluation

After bone tunnels were created, OI and TT models created at 90° were matched to each of 0° and 130° models, and TP models at 130° were matched to each of 0° and 90° models using the point-to-point rigid body registration followed by global registration (Fig. 2a, b). The accuracy of the registration was 0.76 ± 0.49 mm in root mean square. In order to evaluate the graft bending angle (GBA) in 3D, the angle between the femoral tunnel and the virtual graft (the line that connected femoral and tibial footprint of ACL) was measured at 0°, 90° and 130° in each knee model using the Mimics® software (Fig. 3). In order to examine the reproducibility of the measurement method, the intraclass/interclass correlation coefficients (ICCs) were assessed [47]. For the assessment of intraclass reproducibility, measurements of the eight knees after the OI technique were repeated twice by one observer (Y.T.) in a blinded manner with an interval of 1 month. For interclass reproducibility, another observer (S.I.) independently measured eight knees. The intraclass correlation coefficients were high (0.98, 0.96, 0.97), and the interclass correlation coefficients were also high with ICCs 0.97, 0.85 and 0.95 for the measurement of AM, PL and single bundles. For evaluation, GBA difference at each knee angle of single bundle and double bundles, or among three surgical techniques were compared. GBA change amounts from 0° to 90° flexion and from 90° to 130° were calculated as ΔGBA, and ΔGBA were also compared among the three surgical techniques. This study was approved by the Institutional Review Board (IRB) of Kyushu University (ID:24-108), and all subjects gave their informed consent before they were included.

Table 1 Tunnel positions at femur and tibia according to the quadrant method [4, 52]

Femoral side	Outside-in	Trans-portal	Trans-tibial
AM-bundle			
Depth	24.0 ± 5.6	24.0 ± 5.6	33.2 ± 4.6**
Height	20.2 ± 6.2	20.2 ± 6.2	29.6 ± 9.0**
PL-bundle			
Depth	34.9 ± 6.6	34.9 ± 6.6	36.5 ± 2.7
Height	50.7 ± 7.1	50.7 ± 7.1	55.0 ± 5.2
Single bundle			
Depth	28.8 ± 5.5	28.8 ± 5.5	33.6 ± 3.6
Height	35.4 ± 6.6	35.4 ± 6.6	41.1 ± 6.9

Tibial side	AP	ML
AM-bundle	30.6 ± 4.3	51.0 ± 3.4
PL-bundle	47.8 ± 4.8	51.5 ± 2.3
Single bundle	39.3 ± 4.7	51.4 ± 2.9

The values are presented as the mean ± standard deviation (%)

For femoral side, depth = (distance from the posterior edge to tunnel centre along Blumensaat's line/total length of the lateral condyle) × 100 %. Height = (distance from Blumensaat's line to tunnel centre/total height of the intercondylar roof) × 100 % [4]. For tibial side, same tunnel positions were used throughout the three techniques. AP = (distance from anterior edge to tunnel centre/anteroposterior length of the tibia plateau) × 100 %. ML = (distance from medial edge to tunnel centre/mediolateral width) × 100 % [52]

** $p < 0.01$ compared with outside-in and trans-portal technique

Statistical analysis

A repeated-measures analysis of variance (ANOVA) was used for the comparison of GBA changes with knee motion and three surgical techniques, or three bundles of AM, PL and single bundles. Paired t test was used to analyse differences between two OI techniques. Power analysis was performed from our sample data on ANOVA (group number = 3, $n = 8$, between class variance = 26, within class variance = 20, significant level = 0.05) to indicate the power was 0.97, considered enough to address our questions. The JMP® 9 software programme (SAS Institute Inc., Cary, NC) was used for the statistical analysis.

Results

The graft bending angle (GBA) changed significantly with the knee joint motion in each surgical technique ($p < 0.001$) (Fig. 4). In particular at full extension, the graft bending was prominent and the angle reached as high as 94.3° for AM and 84.6° for PL-bundle in OI technique, and 83.1° for AM and 83.0° for PL-bundle in TP techniques. In TT technique, although the graft was almost linear at 90° knee flexion, it showed substantial increase up to 70.0° for AM ($p < 0.001$) and 77.2° for PL-bundle ($p < 0.001$) at full extension. When single-bundle reconstruction was simulated and compared with double-bundle grafts, single-bundle graft did not show a clinically significant decrease in GBA, except for when compared with PL-bundle at 130° by OI ($p < 0.05$) and TP ($p < 0.01$) techniques. In TT technique, PL-bundle at extension showed higher GBA than AM-bundle for every case, but it was not statistically significant (n.s.).

Comparison results of GBA among three techniques are shown in Table 2. Compared with TT technique, both OI and TP techniques revealed significantly high GBA in AM-bundle and in single bundle at 0° and at 90° flexion. In addition, OI technique showed higher GBA in AM-bundle at 0° and 90° flexion than in other two techniques. This tendency was similar in single bundle created by OI technique. In terms of GBA change, ΔGBA from knee 0° to 90° flexion was largest in TT technique ($p < 0.001$), followed by TP and OI techniques, and ΔGBA from 90° to 130° flexion was also larger in TT than in other two techniques ($p < 0.001$).

The influence of locating femoral exit 1 cm proximally in OI technique is shown in Fig. 5. Proximal femoral exit decreased GBA of each double-bundle grafts and the single-bundle graft about 15° in mean both at 0° ($p < 0.01$) and 90° flexion ($p < 0.01$). GBA of AMB at 130° flexion was also decreased ($p < 0.05$) by changing the femoral exit location proximally.

Discussion

The most important finding of the present study was that the graft bending angle (GBA) varied largely during knee motion and the bending was considerably steeper at full extension after simulated anatomic ACL reconstruction.

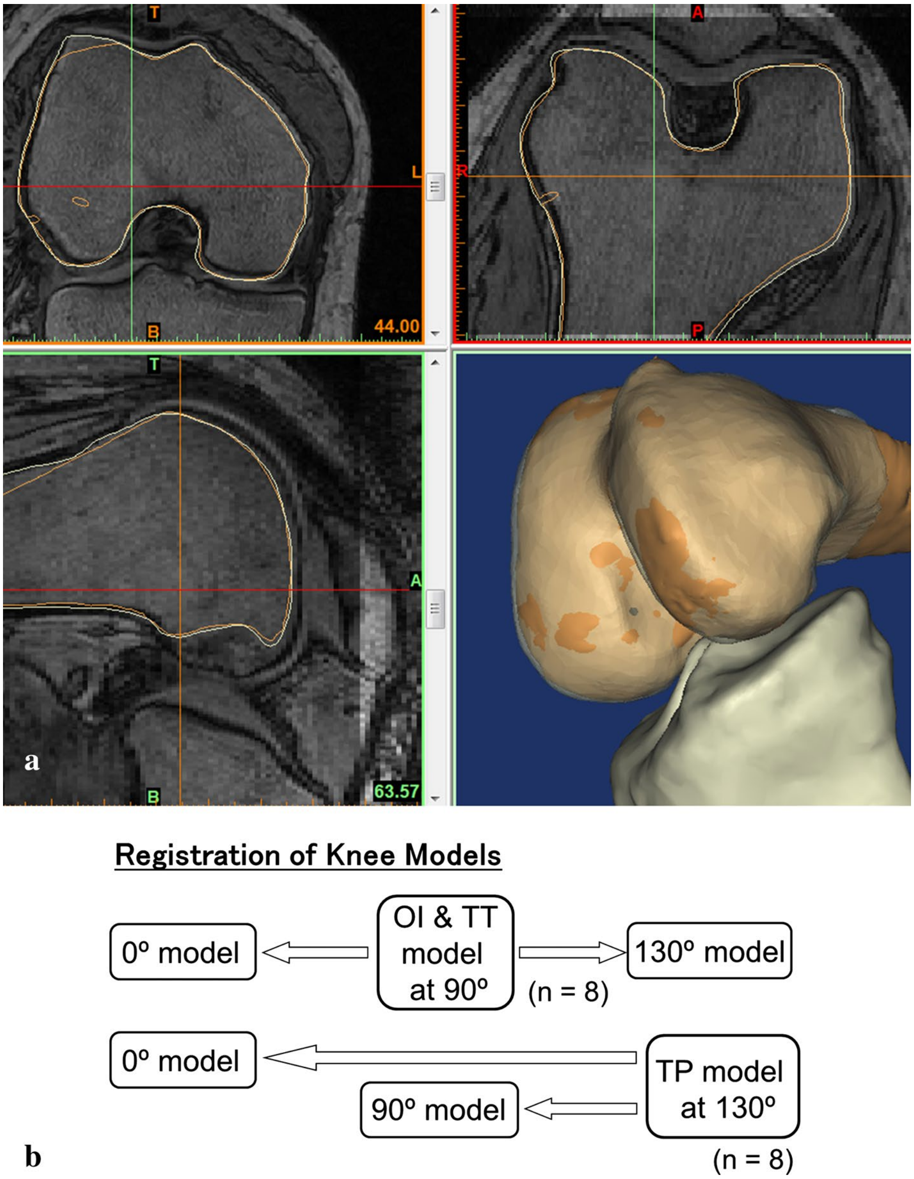

Fig. 2 **a** Bone tunnel drilled model (*brown*) was matched onto other knee flexion angle model (*white*) using point-to-point registration and global registration. **b** The outline of registration is shown. Outside-in (OI) and trans-tibial (TT) models created at 90° were matched to 0° and 130° models. Trans-portal (TP) models created at 130° were matched to 0° and 90° models

The GBA for AM-bundle in double-bundle reconstruction was significantly higher in outside-in (OI) and trans-portal (TP) techniques than in trans-tibial (TT) technique at full extension and 90° flexion. In addition, single-bundle reconstruction with tunnel position on AM-PL centre did not sufficiently decrease the bending steepness. Even in TT technique, GBA for PL-bundle at extension was almost 80° and ΔGBA was substantially larger than other two techniques. This means that the reconstructed graft makes almost a right-angled turn at the femoral tunnel aperture, and therefore high stress between the bone and the graft are suggested at full extension after anatomic ACL reconstruction.

Since tunnel position is crucially important for ACL reconstruction in order to restore normal knee kinematics and to achieve satisfactory clinical outcomes [7, 27, 45, 55, 56, 60], we do not think it is a solution to compromise anatomic placement of graft tunnels. Currently, OI and TP techniques are popular techniques for drilling femoral tunnels in anatomic ACL reconstruction [8, 9, 12, 20, 25, 29, 30, 32, 34, 51, 54, 56], and modified TT technique has been also reported to achieve anatomic placement of the grafts within ACL footprint [14, 58, 59]. Recent studies on GBA evaluated by post-operative CT have reported that OI technique resulted in more steep GBA than in TP technique, with about 80° GBA by OI technique [23, 40, 50], and these results were similar to our findings at full extension. GBA in TP group from these clinical reports were about 70° and the reason of about 10° of decrease from our results might be due to the difference in deep knee flexion angles and location of accessory medial portals between clinical cases with variation and our simulation cohort. Another study by post-operative CT demonstrated milder GBA in TT group than in TP group, and this was

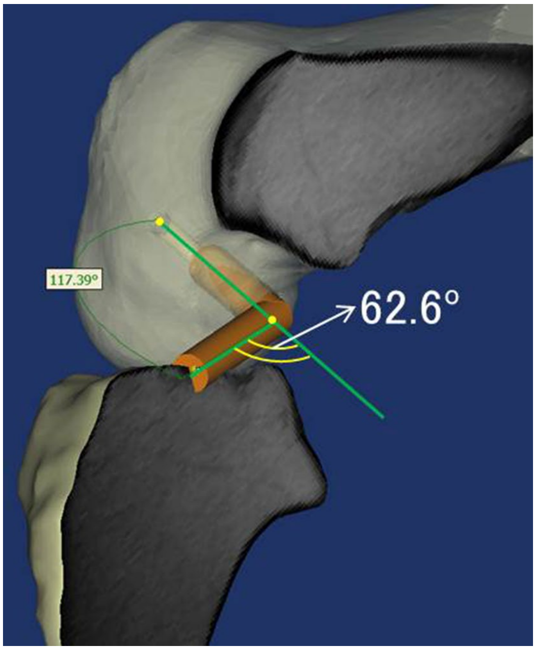

Fig. 3 Measurement of graft bending angle (GBA) in 3D is shown. The angle between the femoral tunnel and the virtual graft was measured as GBA by identifying femoral exit, femoral and tibial apertures in DICOM processing software Mimics®

consistent with our results [57]. There was a tendency that TT technique would reduce the bending angle for AM and single-bundle grafts, although it was still as high as 70° and GBA of PL-bundle in TT technique was even higher in our series.

One of the characteristics of OI technique is that it enables shifting the location of femoral tunnel exit freely with intra articular apertures kept in the anatomic footprint [20, 30, 32]. In our study, more proximal positioning of femoral exits was partly effective, showing GBA decrease for each graft of double-bundle and single bundle at 0° and 90° flexion. The femoral exit location was shifted only 1 cm proximally in the alternative OI model because over 2 or 3 cm of proximal shift could increase the risk of damaging posterior cartilage or lateral soft tissue such as Kaplan fibres, and cortical button fixation failures [32, 38]. Physiologically, as AM-bundle and single-bundle grafts have more tension at 90° flexion [2, 3, 43], reducing the GBA at this flexion angle has a clinical applicability. However, the GBA was still steep enough at full extension, even with this method in OI technique. A previous study using post-operative 3D-CT has reported that more anterior location of femoral exits by OI technique were correlated with higher GBA at knee extension after anatomic ACL reconstruction, and they showed TP technique creating femoral exits at around lateral epicondyle level in anterior/posterior position in lateral view resulted in milder GBA [50]. Thus, combination of appropriate anterior/posterior and proximal/distal location of femoral exits might reduce graft bending steepness in anatomic ACL reconstruction. Specifically, femoral exits in OI technique should be located a little anterior to lateral epicondyle not to damage neurovascular and cartilage tissues [30, 32], but in addition, they should be located 1 to 2 cm proximal and not too anterior to lateral epicondyle in order to reduce GBA.

The novelty of the present study is that this is the first study that 3D GBA change is analysed during knee motion in living human subjects. Most of the previous studies analysed GBA at only one static phase of CT examined [23, 40, 46, 50, 57]. Nishimoto et al. [36] first reported 3D graft bending angles at every 10° knee flexion change using seven cadaveric knees, and our cases exhibited similar changing pattern of GBA as this cadaveric study. One of the advantages of computer simulation model is that it is possible to compare two or three different techniques directly in identical cases under the same conditions. This merit is not necessarily obtained in cadaveric or clinical studies. In addition, it has less confounding factors and it can simplify the factor that involves the specimen.

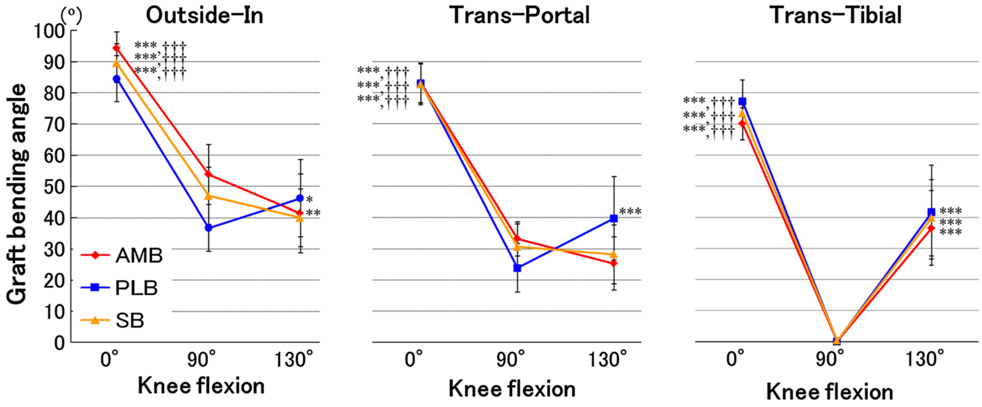

Fig. 4 Graft bending angle changes with knee motion are shown. *,**,***$p < 0.05$, $p < 0.01$ and $p < 0.001$ respectively, compared with 90° in each graft. $^{†,††,†††}p < 0.05$, $p < 0.01$ and $p < 0.001$ respectively, compared with 130° in each graft

Table 2 Comparison of graft bending angles among three techniques

	0°	90°	130°
AM-bundle			
Outside-in	94.3 ± 5.2***,††	53.9 ± 9.6***,†††	41.4 ± 12.6†††
Trans-portal	83.1 ± 6.5**	33.2 ± 5.4***	25.3 ± 8.6**
Trans-tibial	70.0 ± 5.2	0.2 ± 0.5	36.5 ± 12.0
PL-bundle			
Outside-in	84.6 ± 7.4	36.7 ± 7.5***,††	46.2 ± 12.3
Trans-portal	83.0 ± 6.3	23.9 ± 7.8***	39.8 ± 13.3
Trans-tibial	77.2 ± 7.0	0.2 ± 0.3	41.6 ± 15.0
Single bundle			
Outside-in	89.5 ± 6.2***	47.0 ± 9.1***,†††	40.0 ± 9.2††
Trans-portal	83.0 ± 6.7*	30.6 ± 7.3***	28.2 ± 9.5**
Trans-tibial	73.5 ± 3.3	0.3 ± 0.6	39.8 ± 12.2

The values are presented as the mean ± standard deviation

* $p < 0.05$; ** $p < 0.01$ and *** $p < 0.001$ compared with trans-tibial technique

† $p < 0.05$; †† $p < 0.01$ and ††† $p < 0.001$ compared with trans-portal technique

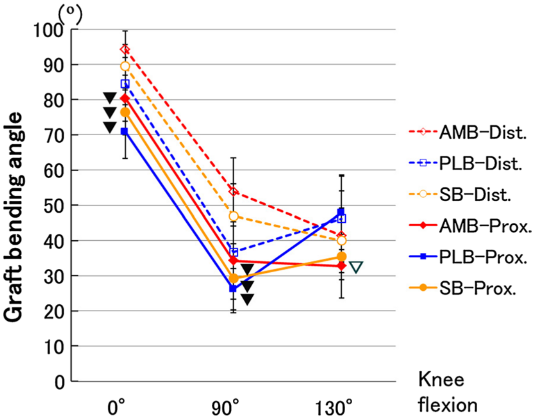

Fig. 5 Outside-in (OI) technique with more proximal (Prox.) femoral exit showed decrease of graft bending angle at knee extension and 90° knee flexion, compared with standard OI technique with femoral exit in distal (Dist.) position. *inverted filled triangle* $p < 0.01$ and *inverted open triangle* $p < 0.05$ compared with the standard OI technique

One limitation of this study is that it is a simulation study and cannot follow the post-operative clinical effect of steep graft bending at the femoral tunnel aperture. A clinical study with follow-up data showing bone tunnel enlargement, or MRI findings of the graft damage or healing, would be needed to discuss the actual stress on the graft due to the steep bending angle. Another limitation is the small sample size of this study. However, the prior power analysis demonstrated enough power to detect the differences among surgical techniques, three kinds of grafts and knee flexion conditions. Single bundle in our study was designed to have centre-to-centre tunnel position [13], whereas some surgeons might create it in AM to AM positions [21]. AM-bundle in our double-bundle ACL reconstruction models could be considered as single-bundle reconstruction with AM to AM positions, but it showed no GBA difference with centre-to-centre single bundles in any technique.

With regard to the clinical relevance, steeper GBA may suggest high stress on the reconstructed graft at the femoral tunnel aperture at full extension after anatomic ACL reconstruction.

Conclusion

Graft bending angle (GBA) changed substantially with knee motion after simulated anatomic ACL reconstruction. Considerably steep graft bending was exhibited at full extension. Outside-in and trans-portal techniques significantly increased GBA of AM-bundle and single bundle at 0° and 90° knee flexion compared with trans-tibial technique, whereas trans-tibial technique demonstrated larger ΔGBA during the knee motion than other two techniques. Single-bundle technique was not effective in reducing GBA, compared with double-bundle technique. In outside-in technique, locating the femoral exit 1 cm proximally from epicondyle was useful for decreasing GBA at knee extension and flexion with the tunnels kept in anatomic position.

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Authors' contributions YT designed the study, performed data collection and analysis. He drafted the manuscript. SI assisted in data collection and evaluation. He revised the manuscript. KO carried out examining the materials and created the 3D knee models. He helped drafting the manuscript. YI assisted in designing the study, grant acquisition and co-supervised the entire research. FF advised the study design and directed all clinical aspects. He examined the validity of data analysis and supervised the entire research.

Compliance with ethical standards

Conflict of interest The authors declare that they have no conflict of interest.

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