Tunnel position and graft orientation in failed anterior cruciate ligament reconstruction: a clinical and imaging analysis

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Abstract

Purpose It has been reported that technical error in positioning the graft tunnel is the most common problem in anterior cruciate ligament (ACL) reconstruction. The objective of this study was to quantitatively evaluate femoral and tibial tunnel positions and intra-articular graft orientation of primary ACL reconstruction in patients who had undergone revision ACL reconstruction. We postulated that this patient cohort had a nonanatomically positioned tunnel and graft orientation.

Methods Twenty-six patients who had undergone a revision ACL were investigated. Clinical magnetic resonance (MR) images prior to revision were analysed. Three-dimensional models of bones and tunnels on the femur and tibia were created. Intra-articular graft orientation was measured in axial, sagittal and coronal planes. Graft positions were measured on the tibial plateau as a percentage from anterior to posterior and medial to lateral; graft positions on the femur were measured using the quadrant method.

Results Sagittal elevation angle for failed ACL reconstruction graft ($69.6^{\circ} \pm 13.4^{\circ}$) was significantly greater ($p < 0.05$) than that of the native anteromedial (AM) and posterolateral (PL) bundles of the ACL (AM $56.2^{\circ} \pm 6.1^{\circ}$, PL $55.5^{\circ} \pm 8.1^{\circ}$).

In the transverse plane, the deviation angle of the failed graft ($37.3^{\circ} \pm 21.0^{\circ}$) was significantly greater than native ACL bundles. The tibial tunnel in this patient cohort was placed posteromedially and medially to the anatomical AM and PL bundles, respectively. The femoral tunnel was placed anteriorly to the anatomical AM and PL bundles.

Conclusions This study reveals that both the tibial and femoral tunnel positions and consequently the intra-articular graft orientation in this patient group with failed ACL reconstruction were nonanatomical when compared with native ACL values. The results can be used to improve tunnel placement in ACL reconstruction.

Introduction

Clinical failure rates of anterior cruciate ligament (ACL) reconstruction have been reported to be between 3.6% and 15% [1–4]. As we encounter a highly active aging population and increasing numbers of primary ACL reconstructions are being performed every year, ACL reconstruction failure may become a recurring problem [5, 6]. The cause of ACL reconstruction failure can be multifactorial and include preoperative knee laxity and range of motion, status of articular and meniscal cartilage, malalignment, integrity of secondary restraints, selection of graft material, surgical technique, postoperative rehabilitation and patient expectations and compliance [6, 7]. Graft failure was reported as one of the main reasons for failed ACL reconstruction [5]. At the time of revision, 22–79% of reconstruction failures were thought to be due to technical errors, with the most common being incorrect tunnel position [5–8]. Marchant et al. [9] reported a nonanatomically positioned graft in 88% of failed ACL reconstructions.

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These errors may have implications with respect to knee stability and graft impingement, resulting in decreased postoperative knee range of motion with possible graft attenuation [5, 10]. The purpose of this study was to quantitatively evaluate the femoral and tibial tunnel positions and intra-articular graft orientation in patients who had a failed ACL reconstruction and were being considered for revision surgery. We postulated that this patient cohort of failed ACL reconstructions had a non-anatomically positioned tunnel and graft orientation.

Materials and methods

Study design

Patients who had undergone revision ACL reconstruction between January 2002 and December 2009 at our institution and had magnetic resonance imaging (MRI) scans of their injured knee after primary but before revision ACL reconstruction were reviewed. We excluded patients with more than one revision ACL reconstruction, multi-ligament-deficient knees or mechanical malalignment in addition to ACL deficiency. Thus, 25 patients [17 men, nine women; mean age 31.8 ± 9.5 (range 16.2–51.9) years] were studied. A detailed medical records review was conducted to delineate demographics, graft type (autograft versus allograft), time from primary to revision ACL reconstruction and chondral changes at the time of revision. Clinical MRIs prior to revision operations but after primary ACL reconstruction were analysed. The Outerbridge classification of grading chondral changes of the knee [11–13] was arthroscopically confirmed during surgery. Three-dimensional models of the knee joint were reconstructed using these images to determine the exact graft placement and orientation. This study was approved by our Institutional Review Board.

Magnetic resonance imaging (MRI)-based 3D modelling

Each patient had his/her affected knee scanned in a relaxed, full-extension position using a 1.5-Tesla MR scanner. The knee was scanned in sagittal, coronal and axial planes in 1.7-mm slice thickness using a 2D spin-echo sequence. MRI size was 160 mm $\times$ 160 mm, with a resolution of 512 $\times$ 512 pixels. MRI analysis and 3D modelling techniques have been previously described [14–18]. Briefly, the MRI of each patient was retrieved and imported into a solid modelling software (Rhino, Robert McNeel and Associates, Seattle, WA, USA) to construct 3D anatomical models of the tibia and femur using an established protocol [19–21]. Bone and bone tunnel contours (from the primary ACL reconstruction) of

the tibia and femur were digitised in each image, and data linked with nonuniform rational B-splines (NURBS) to reproduce tibia, femur and bone tunnel contours in each knee (Fig. 1). The anatomical 3D bony surfaces of the tibia and femur were created from these contours using NURBS. To project the approximate orientation and position of the bony tunnels in the tibia and femur from the primary ACL reconstruction on the 3D models, a cylinder was fitted through the contours of each tunnel and its centre was regarded as the centre of the graft.

Measurements of intra-articular graft angles

Coordinate systems were created using previously established protocols [15, 22]. A line was drawn through the centre of the long axis of the tibia. Perpendicular axes were then drawn in the anterior–posterior (sagittal) and medial–lateral (axial) planes. A Cartesian coordinate system was formed as these axes intersected in the centre of the tibial plateau. This centre was estimated using a line drawn between the centres of two ellipses that approximated the medial and lateral tibial plateau surfaces (Fig. 1). Intra-articular orientation of the primary graft was then determined by drawing a line through the exit position of the tibial tunnel and entry position of the femoral tunnel. Angular measurements of this estimation of the intra-articular portion of the graft were then performed by projecting the line in the axial (deviation), sagittal (sagittal elevation) and coronal (coronal elevation) planes. These angles have been defined in previous studies [23–25].

Measurements of tunnel positions

Intra-articular tibial and femoral tunnel positions (which suggest the intra-articular attachment sites of the graft) were determined where the centre of the cylinders exited the bony surfaces. We adopted the methods of Forsythe et al. [26] to measure tunnel positions. For the tibia, a rectangular coordinate system that bordered the anterior–posterior and medial–lateral borders was made on an axial view of the tibial plateau (Fig. 2a). The tibial tunnel position was calculated as a percentage of the length of the tibial plateau in the anterior–posterior and medial–lateral directions. For the femur, the quadrant method was applied on the medial view of the lateral femoral condyle at 90° flexion of the model. A 4 $\times$ 4 grid was placed referencing off the most anterior edge of the femoral notch roof, corresponding to the Blumensaat line on lateral radiographs, as previously described [26]. The anterior, posterior and inferior edges of the medial wall of the lateral femoral condyle served as the other three borders to make the grid (Fig. 2b). The lines parallel and perpendicular to

Fig. 1 Series of magnetic resonance images (MRI) of failed anterior cruciate ligament (ACL) reconstructed knee was used to build the three dimensional (3D) models of **a** the tibia and **b** the femur. A cylinder was fitted through the contours of the bone tunnels and its centre was regarded as the centre of the graft

Blumensaat line were labeled as (t) and (h), respectively. A variation of this method has been described on lateral radiographs by Bernard et al. [27]

(a) Axial view of tibia

(b) Sagittal view of lateral condyle

Fig. 2 Definition of the **a** tibial and **b** femoral coordinate systems for tunnel position measurement; (t) direction parallel to the Blumensaat line, (h) direction perpendicular to the Blumensaat line. The position of normal anteromedial (AM) and posterolateral (PL) bundles are shown and compared with the position of the tunnel in failed anterior cruciate ligament (ACL) reconstruction. Black dots position of individual tunnels. Red circle average position of tunnels. Blue square position of AM bundle in normal knees. Green triangle position of PL bundle in normal knees

Statistical analysis

Tunnel locations on the tibia and femur were compared with insertions of the native ACL reported by Forsythe et al. [26]. The intra-articular graft orientation was compared with data published by Jordan et al. [24] on anteromedial (AMB) and posterolateral (PLB) bundle orientations of normal knees. A two-sample Student's *t* test with unequal variance and a post hoc Student's Newman-Keuls test were used to determine the statistically significant differences. All statistical analyses were performed using software Statistica (Statsoft, Inc., Tulsa, OK, USA). The level of significance was set at $p \leq 0.05$.

Results

Clinical analysis

Detailed demographic data on the 26 study participants is illustrated in Table 1. From medical records review, mean age and standard deviation (SD) at primary and revision ACL reconstruction was 26.0 ± 9.0 (range 14.4–49.8) years and 31.8 ± 9.5 (range 16.2–51.9) years, respectively. Mean time from primary ACL reconstruction to ACL reconstruction failure was 4.4 ± 4.1 years. Mean time from ACL reconstruction failure to revision surgery was 0.9 ± 1.4 (range 0.1–6.1) years. Mean time from primary to revision ACL reconstruction was 5.9 ± 4.5 (range 0.6–17.6) years.

Twenty-two patients (85%) reported injury leading to their symptoms after primary ACL reconstruction. Chondral damage was documented in 19 patients (73%), and 20 (77%) underwent a partial meniscectomy at the revision procedure. Most commonly, grade III chondral damage was detected at the time of revision (ten patients, 38%). Primary ACL reconstructions were done with autografts in 16 and allografts in 7 patients. Three patients' records did not indicate the type of graft used.

Table 1 Patient demographics

	Male	Female	Early ^a revision	Late revision	Total
Age at primary ACL reconstruction (years)	28.3±8.8	21.5±8.0	21.1±4.7	27.1±9.5	26.0±9.0
Age at revision ACL reconstruction (years)	33.7±10.2	28.3±7.5	22.0±4.6	34.1±8.9	31.8±9.5
Time from primary ACL reconstruction to injury (years)	3.7±2.6	5.7±6.0	0.68±0.18	5.5±4.1	4.4±4.1
Time from injury to revision ACL reconstruction (years)	1.1±1.7	0.8±0.9	0.2±0.1	1.2±1.6	1.0±1.5
Time from primary to revision ACL reconstruction (years)	5.35±3.7	6.8±5.8	0.9±0.2	7.0±4.2	5.9±4.5
History of injury	14	8	5	17	22
Chondral damage at revision ACL reconstruction	13	6	1	18	19
Menisectomy at revision ACL reconstruction	13	7	3	17	20
Autograft at primary ACL reconstruction	9	7	4	12	16
	6 BPTB	5 BPTB	3 BPTB	8 BPTB	11 BPTB
	3 Hamstrings	2 Hamstrings	1 Hamstrings	4 Hamstrings	5 Hamstrings
Allograft at primary ACL reconstruction	6 BPTB	1 Achilles tendon	1 BPTB	6	7
				5 BPTB	6 BPTB
				1 Achilles tendon	1 Achilles tendon

ACL anterior cruciate ligament, BPTB bone-patellar-tendon-bone

^a Within 1 year of primary ACL reconstruction

Graft orientation and tunnel locations

Elevation angle of the graft in failed ACL reconstruction was $75.9^{\circ} \pm 7.5^{\circ}$ in the coronal plane and $69.6^{\circ} \pm 13.4^{\circ}$ in the sagittal plane; deviation angle was $37.3^{\circ} \pm 21.0^{\circ}$ in the transverse plane. Orientation of the failed graft in sagittal, coronal and transverse planes are shown in Fig. 3 and compared with those of normal AMBs and PLBs made based on their anatomical positions on the tibia and femur [26]. Deviation and sagittal elevation angles for the failed ACL reconstructed graft were significantly greater ($p < 0.05$) than those of the native AMBs and PLBs of the ACL [20]. However, the coronal deviation angle was not significantly different in failed ACL reconstructed graft and normal ACL bundles ($p > 0.05$, Fig. 4).

Mean tibial tunnel position was $47.3\% \pm 8.5\%$ in the anterior–posterior direction measured from the anterior edge of the tibial plateau, and $46.6\% \pm 3.7\%$ in the medial–lateral direction measured from the medial edge of the tibial plateau (Fig. 2a). Mean femoral tunnel position was $41.8\% \pm 9.8\%$ measured from the posterior edge of the lateral femoral condyle parallel to Blumensaat line (t direction) and $12.5\% \pm 18.2\%$ measured perpendicular to the Blumensaat line (h direction) (Fig. 2b). Based on our data, the tibial tunnel position in anterior–posterior direction showed moderate correlation with graft orientation in the sagittal plane ($r = 0.58$, Fig. 5a). Also, the tibial tunnel position in the medial–lateral direction was moderately

correlated with graft orientation in the coronal plane ($r = 0.42$, Fig. 5b).

Discussion

Controversy exists regarding the effect of graft position and orientation on knee stability after ACL reconstruction [10, 28–30]. In this study, we used 3D computer modelling and clinical MRIs of patients with failed ACL reconstruction to evaluate the femoral and tibial tunnel positions and intra-articular graft orientation of the primary ACL reconstruction. These data were compared with the intra-articular orientation of native ACL of normal knees in the axial and sagittal planes. Our results indicate that both the tunnel position (Fig. 2) and the intra-articular graft orientation (Fig. 3) of this patient cohort are different from those of native ACL and support our research hypothesis. The tunnel exited close to the centre of the tibial plateau, and the femoral tunnel entered the lateral condyle in box 1b in the 4×4 grid.

In the literature, coronal and sagittal elevation angles of the native ACL are reported in the range of 66° – 74° [23, 31–33] and 43° – 59° [23, 33, 34], respectively. Coronal and sagittal elevation angles measured in this study were similar to those reported by Scanlan et al. on patients with well-functioning ACL reconstruction [25] where these coronal and sagittal elevation angles of the ACL graft were measured to be $80.0^{\circ} \pm 5.0^{\circ}$ and $61.9^{\circ} \pm 7.4^{\circ}$, respectively. The authors

Fig. 3 **a** Coronal elevation angles of the anteromedial bundle (AMB), posterolateral bundle (PLB) and average of that in failed anterior cruciate ligament (ACL) graft. **b** Sagittal elevation angles of the AMB, PLB and average of that in failed ACL graft. **c** Deviation angles of the AMB, PLB and average of that in failed ACL graft

suggested that increasingly vertical graft orientation diminished the graft's capability to replicate native ACL function

Fig. 4 Comparison of sagittal elevation, coronal elevation and deviation angles in failed anterior cruciate ligament (ACL) graft, normal anteromedial (AM) and posteromedial (PL) bundles. Sagittal elevation angle was significantly greater (vertical) in failed ACL reconstruction compared with normal ACL bundles, whereas the coronal elevation angle was not significantly different. Deviation angle of the ACL graft in the transverse plane was also significantly greater than that in the normal ACL bundles. (Data compared with [24])

[25]. Furthermore, Fujimoto et al. [31] found significantly greater coronal graft angles ($79.5^\circ \pm 8.0^\circ$) in an MRI analysis of knees with grade 3 laxity after ACL reconstruction. In general, literature data demonstrate that the ACL graft is more vertical than the native ACL. The sagittal elevation angle of the failed ACL reconstruction graft measured in our study (69.6°) was significantly greater than the literature data of the native ACL [24] (AM sagittal elevation = $56.2^\circ \pm 6.1^\circ$, PL sagittal elevation = $55.5^\circ \pm 8.1^\circ$). The coronal elevation angle of the failed ACL graft (75.9°) was on average greater than that of native ACL (AM coronal elevation = $74.8^\circ \pm 4.0^\circ$, and PL coronal elevation = $72.2^\circ \pm 3.7^\circ$), but it was not significantly different.

Anatomical positions of the AM and PL bundles were reported by Forsythe et al. [26] who found that the tibial positions of the AM and PL bundles were $25 \pm 2.8\%$ and $46.4 \pm 3.7\%$ in the anterior–posterior direction and $50.5 \pm 4.2\%$ and $52.4 \pm 2.5\%$ in the medial–lateral direction, respectively. Also, the femoral positions of the AM and PL bundles were respectively reported at $21.7 \pm 2.5\%$ and $35.1 \pm 3.5\%$ along line t and $33.2 \pm 5.6\%$ and $55.3 \pm 5.3\%$ along line h (Fig. 2b). The tibial tunnel in our patient cohort was placed posteromedially and medially to the anatomical AM and PL bundles, respectively. The femoral tunnel was placed anteriorly (or high) to the anatomical AM and PL

Fig. 5 **a** Sagittal elevation angle of the failed anterior cruciate ligament (ACL) graft versus the position of its tibial tunnel in the anterior–posterior direction. **b** Coronal elevation angle of the failed ACL graft versus the position of its tibial tunnel in the medial–lateral direction

bundles. Kopf et al. [22] compared the tunnel position of the ACL reconstruction with anatomical AM and PL tunnels using computed tomography (CT) scans on 32 well-functioning knees at a mean follow-up of 7.6 ± 6.7 years after transtibial single-bundle ACL reconstruction. Interestingly, they found the tibial tunnel location to be $48.0\% \pm 5.5\%$ in the anterior–posterior direction and $47.8\% \pm 2.4\%$ in the medial-lateral direction. Femoral tunnel locations in their study were $37.2\% \pm 5.5\%$ along line t and $11.3\% \pm 6.6$ along line h [35]. Both these locations are similar to those found in our study.

From a biomechanical engineering point of view, femoral tunnel location depends on tibial tunnel positions in a transtibial tunnel technique [35–37]. Tunnel positions determine graft orientation in the interarticular space. The tibial tunnel position in the anterior–posterior direction affects graft orientation in the sagittal plane, and in the medial–lateral direction affects graft orientation in the coronal plane (Fig. 3a, b). Our data show that the change in tibial tunnel position with respect to anatomical ACL insertion was considerably greater in the anterior–posterior direction than that in the medial–lateral direction (Fig. 2a) and was moderately correlated with the sagittal plane orientation of the graft. Therefore, the orientation of the failed graft in the sagittal view

was significantly more vertical, whereas it was not significantly different in the coronal view. However, we did find a moderate correlation of the graft coronal plane elevation angle and the tibial tunnel medial–lateral position.

Due to the complex geometry of the knee joint, numerous studies report that the transtibial tunnel technique cannot produce a graft that mimics the spatial orientation of the native ACL [35–37]. Therefore, various anatomical ACL reconstructions have been debated in the literature [37] where tibial tunnel independent femoral tunnels have been investigated, such as the medial portal technique, outside-in technique, etc. However, studies [36] also indicate that by an appropriately selected tibial tunnel, a more anatomical femoral tunnel may be achievable so that the graft orientation could be less vertical than using the traditional transtibial tunnel technique.

It should be noted that our study is retrospective. Patient recruitment was limited by the availability of 3D clinical images. In addition, only patients with ACL reconstruction failure after transtibial tunnel technique were available. These factors led to a small sample size. The use of clinical MRI (1.5-Tesla) may have inferior resolution compared with current research MRI (3-Tesla). Future studies should also investigate patients whose knees have been reconstructed using other tunnel techniques. Patient data should be collected from several different institutions to enhance the statistical power when analysing various age groups. A control group with an anatomical ACL reconstruction should be recruited to reveal whether graft position and orientation affect the clinical outcome. Finally, in cases with bone-patellar-tendon-bone (BPTB) graft, the graft is not completely central in the bone tunnel but is positioned to one side. As we could not determine the exact position of the graft inside the tunnel, the centre of the tunnel was used as the best estimation of the graft position within the tunnel.

In conclusion, this retrospective study evaluated tunnel position, intra-articular graft orientation and demographic and clinical findings in patients who underwent revision ACL reconstruction. Using MRI-based 3D modelling techniques, we found that the primary ACL reconstructions in this patient cohort were done with a nonanatomical position and orientation when compared with native ACL data. We concluded that this patient group with a failed ACL reconstruction had a nonanatomical ACL graft position and orientation, but we could not conclude that a nonanatomical tunnel placement/graft orientation will definitely lead to ACL reconstruction failure.

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

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