Radiological evaluation for conflict of the femoral tunnel entrance area prior to anterior cruciate ligament revision surgery

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Abstract

Purpose Anterior cruciate ligament (ACL) revision surgery is a demanding procedure and requires meticulous pre-operative clinical and radiological assessment. In clinical practice the position of the femoral tunnel is identified mainly using plain radiographs (XR). Two-dimensional computed tomography (2D-CT) and magnetic resonance imaging (MRI) are not yet routine imaging methods and are only performed in specific clinical indications or in the scientific setting. Several measurement methods describe the femoral tunnel after ACL reconstruction and indicate ‘ideal or wrong’ placement to the surgeon. The aim of this study is to provide a reliable measurement method to predict potential conflict between the pre-existing and the planned femoral tunnel entrance area (FTEA).

Methods Ten patients with primary ACL reconstruction served as a reference group to describe our desired FTEA. Their femoral tunnel positioning was measured on XR and 2D-CT according to published measurement methods. These results were compared to the FTEA measured with a new technique on 3-dimensionally reconstructed CT-images (3D-CT) based on intra-operative landmarks. Twenty patients requiring ACL revision surgery underwent identical radiological

examination. The mean values of the reference group were compared to each measurement of the patients requiring revision surgery.

Results 3D-CT measurements found potential conflicts in nine out of 20 patients, which all proved to be true during arthroscopic revision surgery. Only one of these patients was identified in all XR and 2D-CT measurements. In 12 out of all 30 patients some measurements on XR or 2D-CT could not be recorded.

Conclusion 3D-CT reconstruction shows the most accuracy in depicting conflict of the pre-existing and desired femoral tunnel prior to ACL revision surgery. The desired FTEA must be defined for each surgeon and his individual technique. In contrast, precision of conventional measurement techniques on XR and 2D-CT is low and does not qualify for this purpose.

Keywords ACL · 3D computed tomography · Femoral tunnel · Revision · Graft positioning

Introduction

The failure rate after ACL reconstruction is estimated as high as in 10–25 % [1–3]. Most reported causes of failure are wrong tunnel placement, biological graft failure, tunnel enlargement leading to graft insufficiency, arthrofibrosis, traumatic re-tear [4, 5], and other causes related to the primary trauma and surgery [2, 6, 7].

Ideal positioning of the graft in the single-bundle technique is a subject of wide debate in the current literature and may differ substantially between surgeons and their technique used [8–12].

Several authors have validated radiological measurement methods on lateral plain radiographs for the assessment of tunnel positioning, all of them orientating on the Blumensaat’s line [13–17]. The clock model

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described by Amis et al. [16] and further-developed by Sommer et al. [14] on tunnel views in 40° of flexion are also frequently used. Rarely, the same methodology has been applied to anterior-posterior projections in full extension [18–20], in tunnel views with 60° of flexion [21] and axial views on CT-scans [15, 22].

The use of 3D-CT or MRI reconstruction has been reported occasionally for the visualisation of the native and the reconstructed femoral insertion on the femur [11, 23–31], and in patients with failed reconstruction [32, 33]. This radiological tool has been validated and shown to be feasible [25].

Clinical and radiological pre-operative assessment prior to ACL revision surgery requires meticulous work-up [1]. ACL revision surgery is a demanding procedure with inferior outcome compared to primary ACL reconstruction [6], and in some cases two stage surgery may be required [34]. The main reason for two-stage revision surgery is conflict of the pre-existing and the planned femoral tunnel leading to tunnel fusion, wall breakage, fixation problems, and bone loss [4]. Radiological examination with X-ray is common practice [4, 35, 36], whereas 2D-CT [4, 36] and MRI [18] are not yet routine. To our present knowledge attempted prediction of conflict between the pre-existing and the planned tunnel has been reported twice [31, 32]; however, it lacked clinical

validation, correlation to intra-operative finding and comparison to conventional radiographs.

Our hypothesis is that 3D-CT improves visualisation of the femoral tunnel positioning compared to 2D-CT and XR and therefore is superior to predict potential conflict of the pre-existing and desired FTEA.

Materials and methods

Participants

ACL reference group

Ten patients after primary ACL reconstruction (single-bundle, two-incision, outside-in technique) served to define the desired and standardised femoral tunnel positioning in ACL reconstruction. All ACL reconstructions were performed by the senior author (RMB). The means of their measurement represent our desired FTEA.

ACL failed group

Twenty patients (32.0 years; range 18.0–56.9) were included for radiological work-up after suffering either from graft

Table 1 Patients with anterior cruciate ligament (ACL)-insufficiency or ACL re-rupture requiring revision surgery

Patient	Age (years)	Gender	Knee	Time after surgery (months)	Primary reconstruction	
					Graft	Bundle technique
1	22.3	Female	Right	85.1	B-PT-B	sb
2	27.8	Male	Right	252.5	B-PT-B	sb
3	22.9	Male	Right	34.7	B-PT-B	sb
4	18.0	Female	Right	68.7	SG-T	sb
5	43.2	Male	Left	21.6	PT	sb
6	56.9	Male	Right	90.8	PT	sb
7	26.8	Male	Left	289.3	SG-T	sb
8	25.8	Male	Left	24.3	SG-T	sb
9	28.5	Male	Left	40.3	B-PT-B	sb
10	45.3	Female	Left	56.8	A-G	sb
11	37.4	Male	Right	118.0	B-PT-B	sb
12	41.3	Male	Left	191.3	B-PT-B	sb
13	35.6	Male	Left	70.6	SG-T	sb
14	32.6	Male	Left	38.3	B-PT-B	sb
15	18.4	Male	Left	71.5	SG-T	sb
16	25.1	Female	Left	280.3	B-PT-B	sb
17	29.1	Female	Left	30.3	Q-T	sb
18	34.7	Female	Right	216.9	B-PT-B	sb
19	21.0	Female	Right	107.3	B-PT-B	sb
20	33.6	Female	Left	291.1	PT	sb

B-PT-B bone – patellar tendon – bone, *SG-G* semitendonus (and gracilis) graft, *A-G* allograft, *sb* single-bundle

Fig. 1 Coordinates in 3-dimensional computed tomography reconstruction (ACL reference group, right knee). **a** Strict dorsal view. Measurement for X_1 and X_2 . **b** Oblique view, measurement for Y_1 and Y_2 is indicated. **c** Oblique axial view. **d** Strict lateral view. Measurement for Z_1 and Z_2 . O point of origin. X , Y and Z three axes (see text), *ACL* anterior cruciate ligament

Fig. 2 Measurement methods in plain radiographs and 2D-CT. **a** Amis et al. [16]. **b** Aglietti et al. [51]. **c** Sommer et al. [14]. **d** Agneskirchner et al. [18]. **e/f** Modified from Amis et al. [16]

Table 2 Measurements on three-dimensionally reconstructed CT-images

ACL reference group		X ₁	X ₁	Y ₁	Y ₂	Z ₁	Z ₂	Conflict	
		–1.77 +/- 1.37	4.65 +/- 0.72	0.32 +/- 0.65	9.94 +/- 0.67	–1.65 +/- 0.55	6.11 +/- 1.34		
ACL failed group	1	–3.07	1.01	0.91	5.10	–1.53	2.08	100 %	
	2	–1.87	4.82	–1.63	7.27	–1.21	4.36	85.4 %	
	3	1.93	3.54	–1.39	4.97	–0.99	2.79	83.5 %	
	4	–5.62	3.78	3.52	12.15	2.25	3.06	60.5 %	
	5	–3.40	3.99	5.38	14.50	–5.85	2.39	44.8 %	
	6	–6.37	2.84	0.00	9.55	–5.79	4.74	42.8 %	
	7	–4.34	1.05	1.57	8.15	–6.31	–1.23	NC	14.9 %
	8	–9.47	0.77	7.61	21.20	–10.09	1.43	2.7 %	
	9	–6.80	2.24	7.56	14.55	–7.01	–2.57	NC	2.2 %
	10	–7.07	1.91	–0.55	9.80	–5.23	–3.12	NC	0 %
	11	–7.35	–1.89	4.30	11.15	–7.92	–3.34	NC	0 %
	12	–10.01	–2.26	6.30	13.25	–9.94	–3.74	NC	0 %
	13	0.00	9.72	4.82	12.60	–9.56	–3.90	NC	0 %
	14	–6.41	3.08	12.80	23.40	–10.95	–3.72	NC	0 %
	15	–6.72	2.11	3.24	9.07	–9.63	–3.11	NC	0 %
	16	–5.23	–2.01	4.14	12.05	–8.01	–3.05	NC	0 %
	17	–5.82	–1.11	3.13	12.05	–5.28	–3.55	NC	0 %
	18	–9.09	–0.79	–3.85	5.93	–5.92	–2.44	NC	0 %
	19	–8.70	1.19	4.82	15.05	–6.12	–2.66	NC	0 %
	20	–9.17	–3.12	6.44	11.35	–11.30	–4.17	NC	0 %

NC no conflict, i.e. not interfering with reference group, ACL anterior cruciate ligament

Patient 1–9 with intra-operative conflict

insufficiency or re-rupture 124.0 months (21.6–291.1) after primary ACL reconstruction (Table 1).

Radiological measurement

3D-CT

A three dimensional (3D) referencing system (X, Y, Z) based on intra-operative landmarks was developed, with the point of origin 'O' (Fig. 1). The measurements were performed on a strictly dorsal view on the intercondylar notch (for X and Y; Fig. 1a) and on a lateral view on the lateral condyle (for Z; Fig. 1d):

- X: a horizontal line perpendicular to the longitudinal axis of the femoral shaft is drawn. The axis must cross the most lateral point of the most posterior aspect of the intercondylar roof. X₁ represents the most medial point and X₂ the most lateral point of the tunnel.
- Y: parallel line to the longitudinal axis of the femoral shaft through the most posterior changing point of the medial aspect of the lateral femoral condyle and the intercondylar roof. Y₁ represents the most proximal and Y₂ the most distal point of the tunnel on the strict dorsal view.

- Z: line along the inner margin of the lateral condyle crossing X, perpendicular to Y. Z₁ represents the shallowest and Z₂ the deepest point of the tunnel in the strict lateral view.

Conflict was predicted when the pre-existing tunnel had overlapping measurements with the desired FTEA on all three axes (presented in percentages).

The intra-rater reproducibility showed high consistency ($p=0.92$).

Plain radiographs (XR)

Four measurements in three different projections were performed for femoral tunnel positioning (Fig. 2a–c):

- Lateral projections measuring along Blumensaat line [17] (presented in percentages)
- Lateral projections referring to the deep lateral condyle [16] (presented in percentages)
- Tunnel views in 40° flexion [14] (presented in degrees on the clock-model)
- Anterior-posterior projections (presented in degrees on the clock-model)

Table 3 Measurements on plain radiographs and 2D-CT

ACL reference group		Plain radiographs								2D-CT					
		Aglietti et al. [1]		Amis et al. [5]		AP		Sommer et al. [47]		Axial [24]		Coronal		Sagittal [3]	
		37.6 % ± 6.1		45.3 % ± 6.9		46.6° ± 7.4		41.0° ± 7.1		53.1 % ± 9.9		44.6° ± 5.5		33.7° ± 5.7	
ACL failed group	1	35.56 %	NC	56.32 %		45	NC	36	NC	37		47	NC	0.383	
	2	37.33 %	NC	36.92 %		44	NC	50		31		45	NC	N/A	
	3	N/A		N/A		45	NC	39	NC	37		43	NC	N/A	
	4	38.89 %	NC	42.86 %	NC	51	NC	45	NC	43	NC	46	NC	0.357	NC
	5	59.09 %		61.54 %		56		48	NC	44	NC	47	NC	0.417	
	6	29.41 %		44.00 %	NC	37		41	NC	43	NC	28		N/A	
	7	22.58 %		51.28 %	NC	34		38	NC	48	NC	23		0.265	NC
	8	42.42 %	NC	52.38 %		60		58		39		37		N/A	NC
	9	38.46 %	NC	53.75 %		35		25		25		37		0.284	NC
	10	31.94 %	NC	41.51 %	NC	16		21		29		27		0.273	NC
	11	38.20 %	NC	37.78 %		N/A		N/A		18		26		0.329	NC
	12	46.25 %		62.50 %		23		21		16		20		0.445	
	13	45.12 %		57.89 %		24		37	NC	39		36		0.351	NC
	14	54.88 %		53.33 %		50	NC	44	NC	40		50		0.485	
	15	43.48 %	NC	50.00 %	NC	54		38	NC	32		45	NC	0.423	
	16	21.05 %		48.15 %	NC	37		31		9		36		N/A	
	17	43.75 %		43.33 %	NC	50	NC	40	NC	39		29		0.278	NC
	18	37.04 %	NC	44.74 %	NC	14		10		1		3		0.400	
	19	33.33 %	NC	43.24 %	NC	41	NC	23		23		29		0.308	NC
	20	50.00 %		0.69		15		17		3		5		0.591	

NC no conflict, i.e. not interfering with reference group, *AP* anteroposterior, *ACL* anterior cruciate ligament, *N/A* femoral tunnel entrance area (FTEA) could not be identified

Patient 1–9 with intra-operative conflict

To rule out a projection bias of the radiographs, the measurements were performed on 3D-CT reconstructions using a metal frame. Hence, strictly lateral views were available for measurement. A conflict was postulated when three or more measurements were in the range of our reference group.

2D-CT

The femoral tunnel positioning was measured in three planes on 2D-CT (Fig. 2d-f):

- Sagittal plane [18, 36] (in percentages)
- Axial plane [15] (in degrees on the clock model)
- Coronal plane (in degrees on the clock model)

A conflict was assumed when two or more measurements were in the range of our reference group.

2D and 3D computed tomography were performed on a Siemens Somatom Definition Dual Source Scanner (Erlangen, Siemens, Germany 2008) and reconstructed by Inspace software. All imagery was performed in full extension and in 15° of internal version of the foot.

Arthroscopy

All patients of the ACL failed group underwent arthroscopy either for one-step ACL revision surgery or for a two-step procedure. Also, all revision ACL reconstructions were performed by the senior author (RMB). The arthroscopic finding served as gold standard for conflict between the pre-existing and desired tunnel.

Results

ACL reference group

The mean measurements of the FTEA show high consistency in the 3D-CT measurements with only small standard deviations (Table 2). Measurements on XR and 2D-CT however are incomplete. In six out of ten patients lateral XR projections or sagittal 2D-CT scans could not visualize the femoral tunnel (Table 3).

Fig. 3 Plain radiographs and 2D-CT versus 3D-CT reconstruction (patient number 11, right knee). **a** X-ray in anterior-posterior projection with uncertain identification of the femoral tunnel (*arrows*). **b** Correct posterior positioning on 2D-CT sagittal plane. **c** 3D-CT reconstruction on metal window, imitating XR tunnel view projection; identical positioning is shown with the reference group. **d** 3D-CT reconstruction shows too shallow and superior (high-noon) positioning of the femoral tunnel entrance area (FTEA)

ACL failed group

3D-CT reconstruction measurements found nine patients with potential conflict of the pre-existing and the desired FTEA. The conflict was confirmed during arthroscopy. None of the 11 patients without conflict on 3D-CT measurements showed conflict intra-operatively.

Interestingly, none of the patients without conflict of the FTEAs showed conflict along the z-axis, hence all were too shallow in the arthroscopic view (Table 2).

Due to invisibility, two femoral tunnels on one lateral and one antero-posterior XR view and five femoral tunnels on sagittal 2D-CT scans could not be analysed. Of the nine patients

with intra-operative conflict of the FTEA, the measurements on XR of two patients (22.2 %) and the results on 2D-CT of three patients (33.3 %) predicted conflict. In total, the analysis of six patients on XR (30 %) and fourteen patients on 2D-CT (70 %) were identical to the intra-operative and 3D-CT findings.

Discussion

To date three dimensional imaging has been used to define the native femoral footprint of the ACL [29], and to quantify and categorise wrong tunnel placement of primary ACL reconstruction prior to revision surgery [31, 32]. So far, 3D-CT has

Fig. 4 Misleading lateral conventional radiograph, 2D and true femoral tunnel location on 3D-CT

not been compared to other imaging methods and has had no clear diagnostic advantage and no implications for surgery. The FTEA is described for the first time in literature, which can only be measured on 3D-CT reconstruction. By comparing the surgeons preferred ACL femoral positioning with the pre-existing FTEA on 3D-CT, potential conflict can be predicted pre-operatively very accurately. Hence, one- or two-stage procedures can be decided prior to surgery. It also compares for the first time conventional radiographs, 2D- and 3D-CT to locate femoral tunnel positioning. The results presented show that XR and 2D-CT are able to describe the tunnel positioning; however, they fail to describe the FTEA and therefore fail to predict potential tunnel fusion in revision surgery.

Standard XR projections after ACL reconstruction are frequently performed and suggested by several authors [7, 19, 37–40], although the femoral tunnel may not be visualised [14, 36], or may even be mistaken for other bony structures (Fig. 3) [36]. Another weakness of X-ray is the superposing effect of different tissues and structures. Hence, despite the femoral tunnel crossing the Blumensaat line posteriorly on X-ray and 2D-CT, 3D-CT may reveal too shallow or high noon positioning (Figs. 3 and 4). Other factors such as condylar variants, a steep Blumensaat line or rotation of the femur may bias the accuracy in X-ray using the different measurement methods published [13, 14, 16, 17, 41].

The use of 2D-CT has been reported to be advantageous to define tunnel widening [39, 42] and to interpret femoral tunnel positioning compared to X-ray [36, 39]. Our results show that measurements on 2D-CT add some information about potential conflict of the FTEAs; however, similar measurement bias as in X-ray are encountered (Figs. 3 and 4).

Too shallow positioning of the femoral tunnel is the most frequent mal-positioning of the femoral tunnel [7, 32, 43] and was found in 12 out of 20 of our patients requesting ACL revision surgery compared to our desired anatomical FTEA. Four patients with too shallow positioning were not detected in lateral X-ray projections (33.3 %) and seven were missed on sagittal 2D-CT planes (58.3 %; Table 3). This is also the most frequent malpositioning in the literature and may be due to the trans-tibial technique [8, 12, 44] and due to the attempt

by the surgeon to prevent posterior wall breakage by approach through the antero-medial portal [43].

Therefore, X-ray and 2D-CT are not precise means to evaluate the FTEA and depict potential conflict.

Using 3D-CT reconstruction, even minor conflict is depicted. It remains, however, unclear as to how much conflict can be tolerated. Due to the pressfit bone block technique used for revision surgery in this study [45], values above 12 % overlap did not require two-stage surgery (Fig. 5).

Our results show that the clock model mainly used on X-ray is highly dependent on projection angles and knee flexion. This is in accordance with the findings in a cadaver study by Steckel et al. [46]. Femoral tunnel positioning of the ACL may markedly differ from the most frequently performed anterior-posterior and tunnel views on X and between axial and coronal planes on 2D-CT. Arnold et al. [47] have questioned its precision and the high inter-individual differences. The main problems of the clock model are its application and anatomical variations of the notch in width and depth leading to major differences in size of the clock, besides the visibility of the tunnels. In addition, in the case of revision surgery, notch plasty might have been performed during primary surgery, hence increasing the notch and the clock size dramatically making this measurement method highly inaccurate. Its use can therefore no longer be recommended (Fig. 4).

The following three aspects should be considered with the new 3D-CT measurement technique: (1) the validation of the desired FTEA has to be defined individually, since tunnel positioning and tunnel width differ due to different surgical techniques, (2) depending on the femoral tunnel drilling devices, the point of origin may preferably be chosen at the deep edge of the lateral condyle, and ((3) exposure to radiation has to be considered, especially in younger patients. Radiological visualisation however does not require the highest resolution. No more than 0.5 mSv are absorbed, hence less than an X-ray of the pelvis (1.8 mSv). New techniques on 3Tesla MRI might increase bone visibility, making such measurements possible to decrease radiation exposure of the patients in future.

To avoid intra-operative conflict of the two femoral tunnels, some authors suggest resection of the failed graft and

Fig. 5 Minor conflict detected by 3D-CT reconstruction and verified with arthroscopy (patient number 11, left knee). **a** Coordinating system on 3-dimensionally reconstructed CT-images. **b** Minor (subcortical) conflict between the femoral tunnel of primary (pFTEA) and revision ACL surgery (rFTEA). *O* point of origin

reconstruction in high noon position [48]. We believe that no compromise should be attempted in the case of failed ACL reconstruction in an attempt to prevent conflict or two-stage surgery. Ideal femoral tunnel positioning should always be achieved and especially in revision cases. Besides inferior results of knee stability and subjective perception [21, 49–52], it has also been postulated that osseous or ligamentous incorporation may be impaired if graft positioning or tension is inappropriate [53–55].

In conclusion, 3D-CT reconstruction is a reliable tool to predict potential conflict of the femoral tunnel prior to ACL revision surgery with high precision. X-ray and 2D-CT on the other hand are not able to visualise the FTEA precisely and therefore may lead unexpectedly to two-stage revision surgery or intra-operative complications with tunnel fusion. Only in cases of major malpositioning or identical entrance area of the femoral tunnel, may X-ray and 2D-CT may suffice as pre-operative radiological work-up.

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