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Upright MRI in kinematic assessment of the ACL-deficient knee

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ABSTRACT

The ability to quantify *in vivo* femoro–tibial relations in the knee holds great advantage to further patient care. There is little consensus on the optimal weight-bearing environment and measurement method for MRI assessment of *in vivo* knee kinematics. This study set out to establish the optimal method of measuring femoro–tibial relations in an upright, weight-bearing environment in normal individuals and those with ACL deficiency. Upright, load bearing, MRI scans of both knees were evaluated by two methods, flexion facet centre (FFC) and femoro–tibial contact point (FTCP), in order to establish femoro–tibial relations in the sagittal plane throughout different angles of knee flexion. A group of healthy volunteers ($n=5$) and a group with unilateral ACL insufficiency ($n=8$) were studied. Abnormal femoro–tibial relations were found in all ACL-deficient knees ($n=8$): the lateral tibial plateau was anteriorly displaced in extension and early flexion and, coupled with smaller changes in the medical compartment, this constitutes internal rotation of the tibia relative to the femur in early flexion. This study found that the FFC measurement technique holds an advantage over the FTCP technique in terms of validity, repeatability and ease of measurements, allowing detection of kinematic changes such as tibial internal rotation in early flexion in ACL-deficient knees in an upright weight-bearing model. We propose that FFC measurement in an upright, weight-bearing position is a reliable and representative tool for the assessment of femoro–tibial movement.

1. Introduction

An accurate and representative assessment of knee function is a difficult task and various methods have been employed in an effort to grade the kinematics of the knee joint. A robust assessment of femoro–tibial relations would enable knee performance to be quantified in the context of pathology and in response to treatment, with great potential to further patient care.

Gait analysis and radiographic studies are popular; in ACL-deficient knees the tibia has been shown to be anteriorly displaced with excessive internal rotation [1–4]. Both of these imaging techniques have their shortcomings however. Gait studies are inherently flawed as surface markers attached to the skin can be subject to erroneous readings during rapid movement change [5]. Although radiological studies counteract this issue, they require ionizing radiation and are often invasive. Also, they are a representation of the movement of bones as opposed to the differences in the articulating site of the tibiofemoral joint where damage occurs [6].

Magnetic resonance imaging (MRI) is favourably suited to the study of femoro–tibial relations as it allows precise imaging of the medial and lateral compartments of the knee in order to elicit subtle changes in articulation. The kinematics of the knee has been the subject of much scrutiny in both *in vitro* and *in vivo* studies in recent years. The tibial plateau is thought to move asymmetrically during flexion while in articulation with the femoral condyles. The medial plateau stays relatively stable with a minimal amount of posterior movement during flexion while the lateral plateau moves progressively anteriorly correlating to internal tibial rotation during flexion [7,8]. In the context of pathological laxity related to ACL insufficiency, however, the kinematics of the femoro–tibial joint are poorly understood [9,10].

Several approaches to imaging have been explored, ranging from computer aided complex three-dimensional analysis to more simple direct interpretation of MRI scans via measurement techniques. Femoro–tibial relations can be derived from mid-sagittal slices of both femoral condyles, allowing a breakdown of anterior–posterior movement and axial rotation. Two measurement techniques have been explored examining normal and ACL-deficient knees. The flexion facet centre technique (FFC) [8] is based on definition of the centre rotation of the posterior femoral condyle, and the femoro–tibial contact point technique (FTCP) [11] maps the articulation position of joint surface contact (Fig. 1). Translation of the joint is defined by both techniques in reference to the posterior tibial plateau. Both techniques are believed to be valid and repeatable but a consensus on the

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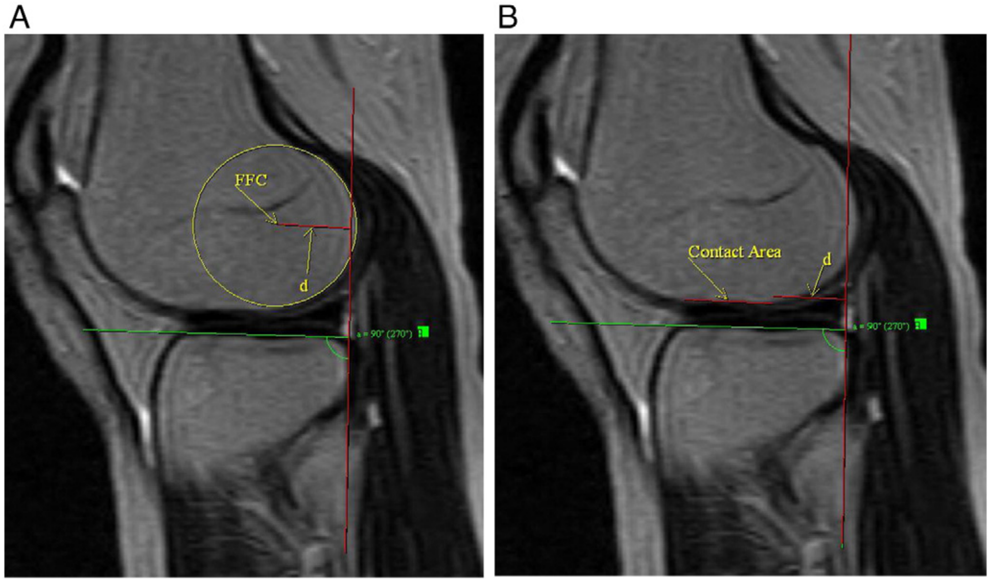

Fig. 1. Measurement of the femoro–tibial relationship. (A) FFC measurement of the lateral condyle of an extended knee. Measurement of d is taken from the posterior tibial cortex in parallel with the tibial plateau. (B) FTCP measurement of the lateral condyle of an extended knee. The midpoint of the contact area is measured from the posterior tibial cortex, d.

superior technique is yet to be explored. Interestingly, both methods produced varying results when employed with ACL-deficient patients [10,12]. With the limited number of studies conducted, kinematic ACL-deficient data is sparse, and a crucial difference between studies is the weight-bearing environments during scanning. The traditional closed-tunnel MRI scanner does not allow adequate weight-bearing, and is therefore unlikely to mimic the *in vivo* changes in the knee. In the presence of pathological laxity, particularly after ACL injury, the need for an adequate weight-bearing simulation has perhaps been overlooked in previous MRI studies. The use of a leg press device did not appear to affect anterior displacement in ACL knees in one MRI study [10]. However, a radiographic study has shown a substantial increase in anterior tibia translation in ACL-deficient knees when converting from non-weight-bearing to an upright weight-bearing position [13].

We wished to evaluate the relative validity and repeatability of FFC and FTCP measurement techniques in the context of normal individuals and those with pathological laxity (ACL rupture) in an upright open MRI scanner that allows imaging in genuine weight-bearing situations. The aim was to determine how ACL deficiency affects femoro–tibial relations and secondly to define the most reliable technique for assessment of relative femoro–tibial translation in this scanning environment.

2. Methods

2.1. Subjects

Healthy volunteers with no complaints or previous surgery to either knee were sought from a group of medical students. These volunteers were asked to give appropriately informed consent after considering an information sheet describing the study.

Patients with confirmed unilateral ACL ruptures who had been reviewed by the senior author and listed for reconstruction surgery were approached to participate. These patients were eligible if they were aged 17–55 and were being treated for an isolated ACL rupture, with or without meniscal pathology. Patients with multiple ligament injuries were excluded.

Ethical approval was granted by the North of Scotland Research Ethics Committee.

2.2. MRI scanning

All MRI scans were performed using the Upright™, Positional™ MRI scanner (FONAR Corp., Melville, NY). The unique open environment of the scanner allows for upright weight-bearing positioning, e.g. squatting, providing exceptional possibilities for imaging of the musculoskeletal system. In this study patients were positioned standing on the positional MRI bed at a reclined angle of **30°**, thus adopting a representative weight-bearing stance that could be maintained during image acquisition (Fig. 2). Knees were positioned shoulder width apart and feet facing forward. A 45° abdomen torso coil was used around both knees to allow simultaneous imaging of both knees.

T2 weighted images in the sagittal plane were taken (TR = 1638 ms, TE = 132 ms). Scanning of the entire knee was initially piloted but proved unsuitable due to time constraints. The midpoint of each condyle was, therefore, determined via an initial 'scouting' transverse image scan in agreement with the radiographer and researcher (Fig. 3). Three slices, each 4.5 mm apart, were then taken of each condyle aligned in the AP field in relation to the femoral position. From these images, measurements were performed on the scan depicting the best representation of the middle of each femoral condyle, matched respectively for the contralateral knee. Scans were performed with knees at full extension and at increasing increments of flexion of 30°, 60° and 90°, measured on both knees by the researcher using a Goniometer and referencing the midpoint of the joint margin in the sagittal plane (Fig. 2). Previous studies have indicated that although there is variation between individuals, the right and left knee show a near-identical pattern of femoro–tibial relations in the 'normal' individual [11].

Osiris software produced by the University Hospital of Geneva was used to analyse images. This allowed precise measurements to be carried out to within 0.1 mm with the MRI images scaled to correct dimensions.

2.3. Flexion facet centre

The posterior aspect of each femoral condyle has been shown to have a relatively circular structure in the sagittal plane. The centre of this circle can be used as a reliable reference point (the FFC) for the position of each condyle [8]. The size of each FFC was determined for the medial and lateral condyle and matched identically on the

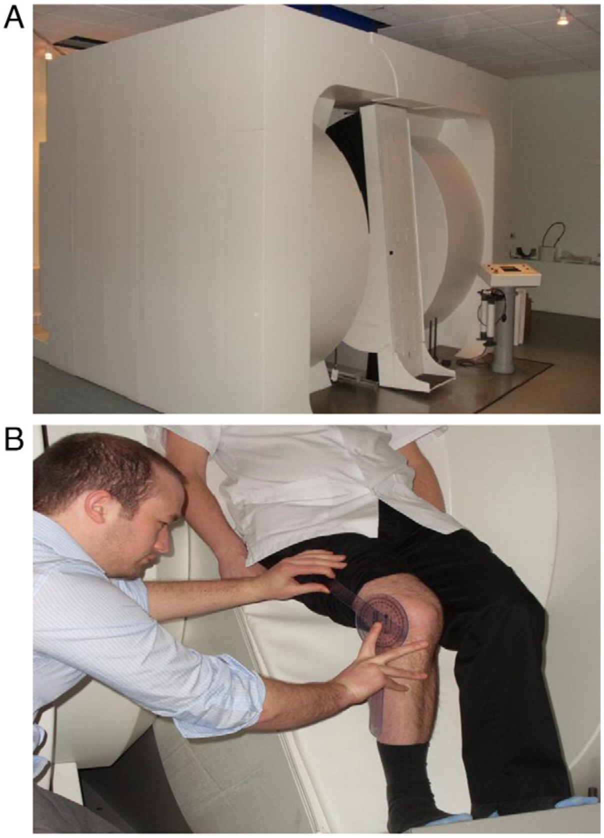

Fig. 2. FONAR positional MRI scanner. (A) FONAR positional MRI scanner. (B) Patient positioned at **60°** of knee flexion in the scanner.

contralateral side, respectively. This was kept consistent for both knees during all angles of flexion. A horizontal line was placed across the tibial plateau, and a line perpendicular to that was dropped to mark the posterior cortex of the tibia. The distance from the perpendicular line to the FFC could then be measured, taken parallel with the tibial plateau surface (Fig. 1). This was performed for the medial and lateral compartments of each knee.

2.4. Femoro–tibial contact points

FTCP measures the difference in sites of articulation at the femoro–tibial joint [11]. The position at which the femoral condyle contacts the tibial plateau is determined for the medial and lateral compartments. A horizontal line was placed across the tibial plateau, and a line perpendicular to that was dropped to mark the posterior cortex of the tibia. The distance from this perpendicular line to the FTCP could then be measured, taken parallel with the tibial plateau surface. Where articulation did not occur at a single point, the centre of the contact plane was recorded as a reference (Fig. 1).

2.5. Statistical analysis

Statistical analysis of the data was carried out using the Statistical Package for Social Sciences (SPSS) version 17.0. MRI scans of the knee were analysed using Osiris software, developed by the University Hospital of Geneva. This software allows manipulation and analysis of MRI scans with correct scaling.

Data was assessed for normality and tests chosen appropriately. For both measurement techniques the respective position of medial and lateral compartments of each knee was compared to the contralateral side at the various increments of flexion. The mean and standard deviation (SD) of each compartment were determined relative to the contralateral side. For statistical comparison the Wilcoxon signed rank test was used. Comparisons were made between:

- The right and left healthy volunteer knees.
- The ACL-deficient knee and healthy contralateral knee.

Reproducibility was assessed by intra- and inter-observer differences. Intra-observer error was determined by the researcher repeating each measurement twice blinded to the previous result, with a minimum of 24 h between each measurement. The mean of the two measurements was used for the final recording. To assess inter-observer error, an experienced orthopaedic surgeon trained in both methods repeated the measurements. A Bland-Altman plot were then constructed.

Correlation between measurement methods was performed using a Spearman's rank correlation coefficient. The level of statistical significance for all tests was taken as $p<0.05$.

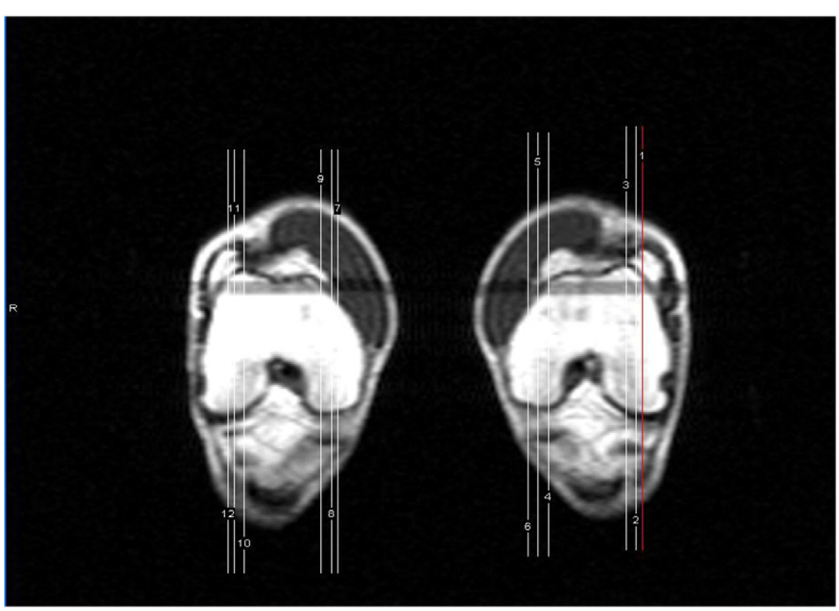

Fig. 3. MRI scouting image: Transverse plane MRI image showing the alignment of sagittal images for both condyles of each knee.

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3. Results

3.1. Subjects

The control group was made up of five healthy medical student volunteers (three women and two men). The patient group consisted of eight sequential patients with ACL deficiency. The mean participant age was 31 years (range 19–43 years) and seven were male. The most common cause of injury was due to football. The average time since the initial ACL injury was 45 months (range 2–132 months). Meniscal tears were present in the majority of participants, three were lateral, two medial and two with both menisci involved as found during arthroscopy at the time of anterior cruciate reconstruction. Arthrometer KT-1000 recordings produced a mean side-to-side difference of 6.5 mm ($n=8$, SD 3, range 0–9.5 mm) of passive anterior tibial laxity. Increased laxity was evident in all patients except one who not show a difference between knees; at examination a painful joint effusion meant the knee was not adequately relaxed. No patient was excluded for pre-existing pathology. One patient had undergone a previous arthroscopy to diagnose the ACL rupture and another patient had suffered from patella tendonitis in the past. No patients refused to participate, and all completed the MRI scanning assessment.

3.2. Volunteer data

Right and left knees showed near-identical measurements for each respective compartment with a mean side-to-side difference FFC of 0.8 mm (SD 0.8, range 0–3.0) and FTCP of 1.5 mm (SD 1.0, range 0–3.6) (Tables 1 and 2). No significant differences were observed between respective compartments at any angle of flexion using the Wilcoxon signed rank test ($p>0.05$). Both techniques observed asymmetry between the medial and lateral compartments. As with previous literature, the medial plateau appears to stay relatively central beneath the medial femoral condyle, while in comparison the lateral plateau moves progressively anteriorly during flexion. This constitutes internal rotation of the tibia in relation to femur during flexion, or external rotation during extension, e.g. screw home mechanism [7,11] (Fig. 4).

3.3. ACL-deficient data

Eight patients underwent MRI scanning. Anterior displacement of the tibia was observed in all ACL-deficient knees in comparison to the contralateral knee.

In the ACL-deficient knee the medial tibial plateau was found to be anteriorly displaced, relative to that of the respective control in the contralateral knee, in extension and during flexion. The FFC measurements (Table 3, Fig. 5) showed that from extension to 60° the tibial plateau was anteriorly displacement by a mean of 2.2 mm (SD 3.0), this displacement resolved at 90° (0.4 mm, SD 4.7, Wilcoxon signed rank test, NS). The FTCP (Table 4, Fig. 5) showed a similar pattern: at extension, the ACL-deficient medial femoral condyle articulated posteriorly on the tibia with a mean of 3 mm (SD 2.6) difference with respect to the control knee (Wilcoxon signed rank test, $p=0.018$). Relatively insignificant changes were observed at 30° and 90°; however at 60° posterior articulation occurred with a mean of 1.9 mm (SD 3.1) of AP difference relative to the normal side.

Excessive anterior subluxation of the lateral tibial plateau was present with both techniques with respect to the control knee. The FFC measurements showed from extension to 60° the plateau was anteriorly displaced by a mean of 4.9 mm (SD 5.3), resolving by 90° (0.4 mm (SD 5.0)). This was found to be statistically significant for early angles of flexion using the Wilcoxon signed rank test (extension $p=0.012$, 30° $p=0.017$). The lateral condyle kept in the same position on the tibial plateau from 0–60° with little evidence of the posterior ‘sliding’ seen in the healthy contralateral knee and volunteers.

The FTCP showed similar results to that of the FFC measurements. From extension to 30° articulation occurred posteriorly on the tibial plateau with a mean difference to the control knee of 5.9 mm (SD 4.1), which was of significant difference at both angles ($p=0.025$ and $p=0.012$, respectively). This reduced to 2.4 mm (SD 4.3) at 60° with minor differences occurring at 90° (0.5 mm (SD 3.9).

The considerable anterior subluxation of the lateral tibial plateau compared to the smaller displacement of the medial aspect indicates excessive internal rotation of the tibia on the femur. This was most evident at extension and low angles of flexion.

3.4. Repeatability of techniques

A random sample of 80 FFC and FTCP measurements was used to determine intra- and inter-observer error.

3.5. Intra-observer error

The mean difference between the researcher's blinded repeats was 0.3 mm (SD 1.0) for the FFC and 0.9 mm (SD 1.6) for the FTCP. No significant difference was observed for either measurement using the Wilcoxon signed rank test (FFC $p=0.812$, FTCP $p=0.361$). The Bland–Altman plot indicates a good agreement for both measurements and produced random scatter pattern with no obvious correlation (Fig. 6). Despite the outliers, small limits of agreement were observed for each technique (FFC 1.997 and −2.056, FTCP 3.140 and −2.960).

3.6. Inter-observer error

The mean difference between the researcher's measurement and the second observer were 1.2 mm (SD 2.0) for the FFC and 0.9 mm (SD 2.6) for the FTCP. This was significantly different for both measurements by use of the Wilcoxon signed rank test (FFC $p=0.000$, FTCP $p=0.025$). The Bland–Altman plot indicates a good agreement for both measurements with a random scatter observed and 95% of the measurements are within the limits of agreements for both techniques (Fig. 7). Larger limits of agreements were observed when compared to the researcher's repeats, with the limits of agreement reaching FFC of 2.623 and −5.077 and FTCP of 6.038 and −4.340.

3.7. Agreement between measurement techniques

Measurements of FFC and FTCP were compared against each other for correlation. The Spearman's rank coefficient gave a result of $r=0.569$ for $n=80$ random measurements samples. When just considering measurements taken during flexion, a random sample of measurements from 30–90° revealed a correlation of $r=0.733$ (Fig. 8).

4. Discussion

This study is the first attempt to establish a robust method for the assessment of femoro–tibial relations during representative weight-bearing. Five healthy volunteers were recruited to demonstrate construct validity. Previous studies indicate that although there is variation between individuals, the right and left knee show a near-identical pattern of femoro–tibial relations in the ‘normal’ individual, in keeping with our data [7,11].

4.1. ACL-deficient data

The medial tibial plateau of the ACL-deficient knee followed a similar pattern of movement relative to that of the control. At early angles of flexion though, it was found to be anteriorly displaced particularly in extension with both techniques, FFC = 2.2 mm and FTCP = 3 mm, which was significant. The lateral tibial plateau was anteriorly displaced from extension to 60° (mean of FFC = 4.9 mm, FTCP = 4.7 mm), these differences were found to be significant with both techniques for the early angles of flexion. The lateral plateau did not exhibit the healthy pattern of posterior sliding seen in normal knees. The greater subluxation of the lateral tibial plateau compared to smaller change in the medial side constitutes excessive internal rotation of the tibia on the femur during early angles of flexion.

Table 1
Mean volunteer FFC measurements.

	Posterior tibial cortex to FFC (mm)							
	0°		30°		60°		90°	
	M	L	M	L	M	L	M	L
Right knee, mean (SD)	22.6 (4.7)	23.8 (5.3)	28.4 (4.4)	22.5 (5.5)	27.3 (2.7)	19.9 (6.2)	25.1 (3.4)	17.0 (3.6)
Left knee, mean (SD)	22.9 (3.9)	24.1 (4.7)	28.7 (4.2)	23.1 (5.5)	27.4 (2.8)	19.7 (5.9)	25.8 (3.0)	16.4 (3.3)
Mean difference (SD)	1.1 (0.5)	1.2 (1.0)	0.6 (0.7)	0.6 (0.6)	0.8 (0.9)	0.6 (0.7)	0.6 (1.0)	1.0 (0.8)
***P* value**	.414	1.000	.157	.102	.783	.458	.197	.109

M, medial condyle; L, lateral condyle.

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Table 2
Mean volunteer FTCP measurements.

	Posterior tibial cortex to FTCP (mm)							
	0°		30°		60°		90°	
	M	**L**	**M**	**L**	**M**	**L**	**M**	**L**
Right knee, mean (SD)	42.8 (4.1)	37.4 (5.2)	32.0 (5.3)	22.3 (5.1)	26.3 (3.9)	17.7 (5.6)	23.4 (5.4)	16.3 (3.9)
Left knee, mean (SD)	43.6 (4.8)	37.9 (5.0)	32.3 (6.1)	22.6 (4.3)	27.3 (2.8)	17.8 (4.9)	23.4 (3.5)	16.7 (3.1)
Mean difference (SD)	1.4 (1.3)	1.5 (0.7)	1.5 (1.3)	0.8 (0.7)	1.5 (1.2)	1.1 (1.0)	1.8 (0.7)	2.0 (0.9)
***P* value**	.465	.500	.893	.713	.345	.500	1.000	.686

M, medial condyle; L, lateral condyle.

Our findings are similar to previous work done with gait and radiographic studies in the ACL-deficient knee whereby anterior displacement of the tibia is present along with excessive internal rotation [1–4]. A previous MRI study of upright weight-bearing ACL-deficient knees also found anterior subluxation of the lateral tibial plateau with relatively small differences in the medial compartment in keeping with our data [9]. Supine scanning found minor changes in the articulation sights of ACL-deficient knees [10]. A leg press device to simulate weight-bearing may not be an adequate representation as no difference was observed between the unloaded knee and that with leg press device [10]. Conversely a radiographic study found a substantial increase in anterior tibial translation in ACL-deficient knees when converting from non-weight-bearing to weight-bearing however [13]. This study may well therefore have inadequate weight-bearing or may have the effects of gravity already stabilising the tibia, thus producing misrepresentative results. The apparent discrepancies found between the limited number of ACL-deficient kinematic studies are, therefore, likely to be attributable to differences in scanning environments. An adequate weight-bearing representation while assessing femoro–tibial relations in the context of pathological laxity appears to be of vital importance. This is emphasised by this findings of ACL-deficient knees in upright MRI scanning in this study and by Logan et al. [9].

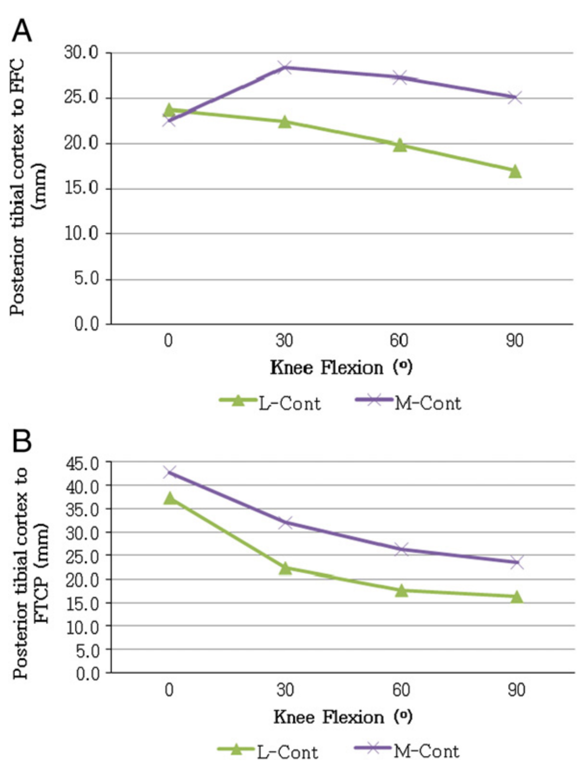

Fig. 4. (A) Line graph showing mean FFC measurements of volunteer right knee. (B) Line graph showing mean FTCP measurements of volunteer right knee. The angle of knee flexion (°) is displayed on the *x*-axis against the distance from the posterior tibial cortex (mm) on the *y*-axis of the respective femoral condyle. The legend demonstrates the different lines represented by the medial and lateral condyle of the control knee (M-Cont and L-Cont, respectively).

The posteriorlateral bundle of the ACL is known to be under its greatest strain between low levels of flexion to extension [14], here serving its primary role to resist anterior translation and internal rotation of the tibia. This correlates well with the findings of excessive internal rotation of the tibia at early angles of flexion. The abnormal subluxation is thought to be a result of the shape of the tibial plateau and the restraint of the posterior horn of the medial menisci on the medial femoral condyle [15]. Our study had a large number of menisci tears, the contribution of which to joint kinematics is complex but is likely to impact the function of the secondary stabilisers [16,17]. Wide variations were observed between patients in the magnitude of anterior displacement and internal rotation. This could reflect the ability of the secondary stabilisers to resist abnormal tibial subluxation after ACL injury.

Imaging studies have recently shown that secondary signs of ACL rupture may aid the MRI imaging of equivocal ACL ruptures [18]. The presence of lateral tibial plateau anterior subluxation was found when the knee was imaged with a splint that produces an anterior force to the tibia. This is consistent with our finding of abnormal tibial rotation in ACL deficiency, although our use of weight-bearing imaging is perhaps more physiological. Our method of weight-bearing FFC grading may also be of use on such occasions, although at this stage we present our method as a research tool and its use in diagnostic scanning remains to be determined.

The long term sequelae of ACL insufficiency has a high incidence of degenerative osteoarthritis particularly in the medial compartment [19–21]. Abnormal kinematics persisting after the principal injury is thought to produce an abnormal loading environment [4,10,22] and risk further meniscal injury [23,24]. The excessive subluxation of the lateral tibial plateau found in our study may also have the effect of producing a shearing force on the medial tibial plateau under the weight of the large medial femoral condyle.

4.2. Assessment of femoro–tibial relations

FFC recordings are a technique employed by several research groups [8,9] and use the posterior femoral condyle in the sagittal plane as a reference point to determine the relative position of the tibial plateau in each compartment of the knee. In order to reduce variability, the researcher determined an appropriately fitting FFC for the medial and lateral condyle for each patient which was matched to the respective side on the contralateral knee. This was kept consistent for all angles of flexion and therefore provided a reliable reference point for each scan. Intra-observer errors were small and insignificant, but inter-observer errors were larger and significant; we believe this is due to differences in scaling of the FFC between observers.

Mapping of FTCP was proposed by Scarvell et al. [11] to show alterations in articulation sites, therefore giving possible insight into the increased degenerative change found in the chronically injured

Table 3
Mean ACL-deficient FFC measurements.

	Posterior tibial cortex to FFC (mm)							
	0°		30°		60°		90°	
	M	**L**	**M**	**L**	**M**	**L**	**M**	**L**
ACL, mean (SD)	21.2 (2.6)	19.7 (4.5)	28.3 (4.8)	19.8 (6.6)	28.9 (4.1)	20.3 (5.8)	28.7 (3.5)	17.4 (4.7)
Control, mean (SD)	23.5 (2.5)	27.2 (2.2)	30.7 (4.3)	25.0 (4.5)	30.7 (3.7)	22.2 (2.4)	29.1 (2.2)	17.1 (4.6)
Mean difference (SD)	2.3 (3.2)	7.5 (4.5)	2.4 (4.2)	5.2 (3.9)	1.8 (2.9)	1.9 (6.2)	0.4 (4.7)	-0.4 (5.0)
***P* value**	.123	.012	.123	.017	.141	.575	.753	.944

M, medial condyle; L, lateral condyle.

ACL-deficient knee. On closer inspection of the method, however, the authors have simplified a difficult task. They claimed a single articulating point could be determined at all angles of flexion in the knee. This was problematic as articulation often appeared to occur over an area rather than a single point. The reduced image quality obtained from the 'open' MRI scanner in this study may have further complicated this issue. When this occurred the middle of the articulating site was estimated as a reference point. This produced a more subjective approach to FFC recordings, although intra-observer differences were still not significant. Inter-observer differences were of the same magnitude (0.9 mm), but were significant.

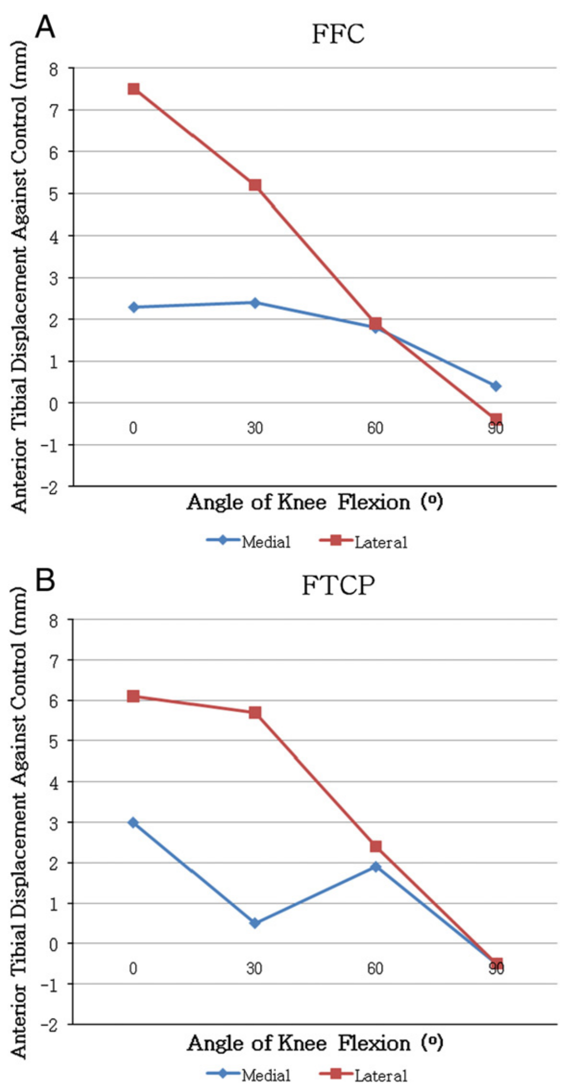

Fig. 5. (A) Line graph showing mean FFC measurements of ACL-deficient knee against control. (B) Line graph showing mean FTCP measurements of ACL-deficient knee against control. The angle of knee flexion (°) is displayed on the *x*-axis against the difference of anterior displacement of the tibia in the ACL-deficient knee against the recordings of the control knee for the medial and lateral compartments.

Although both techniques showed small variation when performed by the principal researcher a significant difference was observed when performed by a second observer. This risk of subjectivity has not been adequately addressed by previous studies. Scarvell et al. incorrectly used correlation to assess observer error as opposed to a Bland–Altman plot, which may have given a falsely high indication of repeatability [11]. With a single researcher performing all measurements it is believed that the intra-observer error gave an acceptable level of confidence.

The correlation between FFC and FTCP measurement techniques was fair across 80 randomly selected measurements ($r = 0.569$). Both techniques measure different landmarks within the femoro–tibial joint. Using the FFC as a reference point, flexion of the tibia is reflected by an initial anterior movement of the FFC on the tibial plateau. Conversely, FTCP display a continuous posterior articulation throughout flexion. This may explain the poor correlation when including angles of extension. When full extension measurements were removed this increased to $r = 0.773$, indicating a strong positive association.

Measurements were carried out on Osiris software which allowed magnification of the images with precise measurements to 0.1 mm. Accurate measurement without the need to transfer the image to acetates, as used in other studies [9], reduced the risk of incorrect scaling and measurement inaccuracies.

The design of the FONAR^{TM} 'open' MRI scanner compromises on magnetic strength (0.6 T), resulting in longer scan time and reduced image quality when compared to a conventional supine MRI scanner. Therefore only essential sagittal images across each condyle were captured, guided by transverse scout images. This may have caused variability in image placement and when selecting the scan for measurement. Patient positioning using a rigid brace device to hold the leg in different increments of flexion was considered but discounted as realistic weight-bearing could not be achieved with the leg held in position. Instead, angles of flexion were determined using a Goniometer, as used previously [9]. This method allowed measurement of knee flexion, although estimating the correct angle may be prone to error. A more thorough 3D assessment using coronal images would have been useful; however this would have almost doubled an already lengthy scan time.

Our understanding of the *in vivo* kinematics of the knee in pathology and in response to treatment strategies remains sparse [10,22]. Different surgical interventions and post-operative recovery could be explored with such a method as outlined here. A kinematic comparison of single- against double-bundle anterior cruciate reconstructions would be one possible example. Additionally, the kinematic effect of meniscal tears and subsequent surgical intervention remains largely unexplored [15]. The ability to grade such findings holds potential to determine effective treatments with the ultimate aim to further patient care.

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Table 4
Mean ACL-deficient FTCP measurements.

	Posterior tibial cortex to FTCP (mm)							
	0°		30°		60°		90°	
	M	L	M	L	M	L	M	L
ACL, mean (SD)	39.0 (4.4)	38.4 (7.8)	34.5 (4.8)	22.0 (5.6)	30.3 (3.3)	20.4 (4.4)	28.7 (2.7)	20.0 (5.5)
Control, mean (SD)	42.1 (5.0)	44.5 (6.0)	35.0 (3.9)	27.7 (4.9)	32.2 (3.2)	22.8 (3.8)	28.2 (2.3)	19.5 (4.1)
Mean difference (SD)	3.0 (2.6)	6.1 (5.3)	0.5 (2.5)	5.7 (3.0)	1.9 (3.1)	2.4 (4.3)	-0.5 (3.9)	-0.5 (3.9)
***P* value**	.018	.025	.398	.012	.093	.123	.674	.484

M, medial condyle; L, lateral condyle.

5. Conclusions

This study demonstrated large differences in ACL-deficient knees in terms of anterior displacement and disturbances in rotation when compared to that of healthy knees. The comparison of two measurement techniques found that FTCP measurement incurred a more subjective assessment and did not always appear to demonstrate the true site articulation, while the FFC recordings were easier to obtain with greater repeatability, indicating they hold an advantage over FTCP. This is the first time these two methods have been compared against each other.

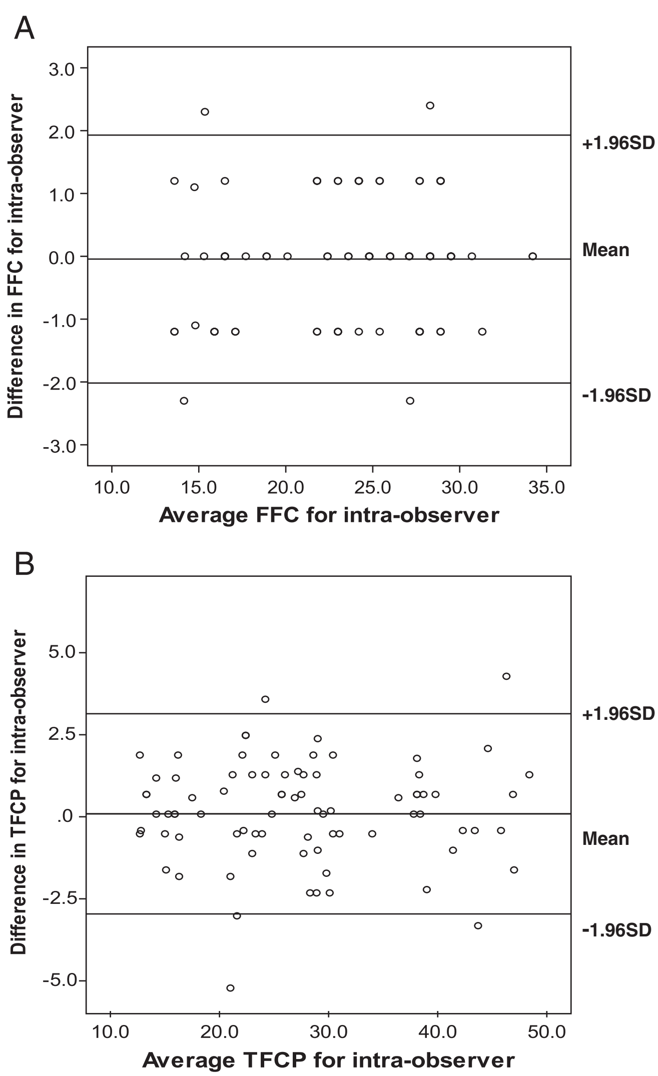

Fig. 6. Bland and Altman plot showing the comparison of intra-observer error. (A) Flexion facet centres ($p = 0.812$). (B) Femoro–tibial contact points ($p = 0.361$).

Our study also highlights the importance of upright weight-bearing with regards to pathological kinematic studies. We propose that FFC measurement in an upright, weight-bearing position is a reliable and representative tool for the assessment of femoro–tibial movement.

6. Conflict of interest

No conflicts of interests are declared.

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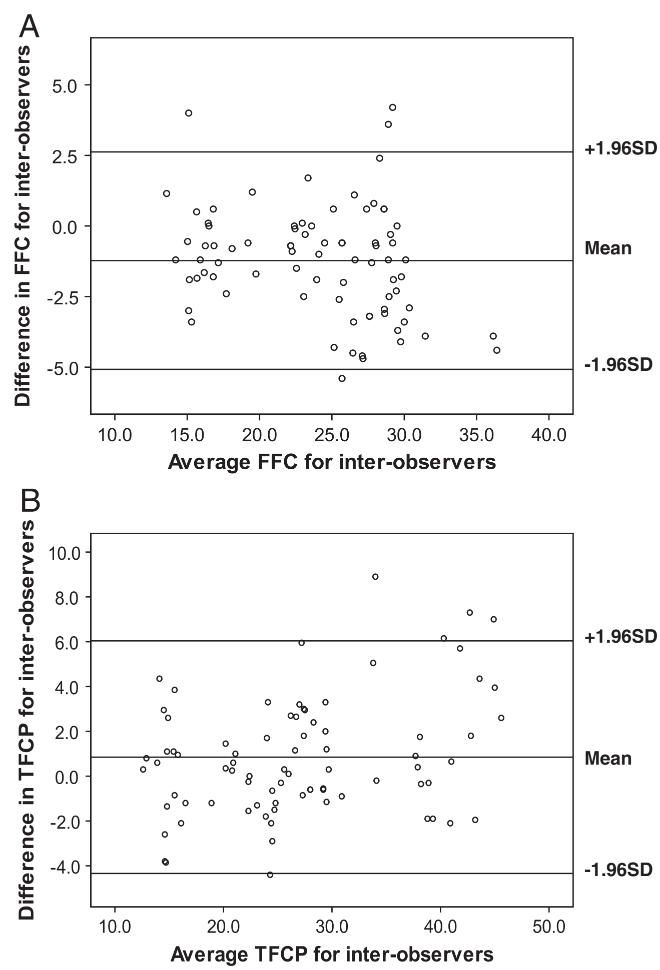

Fig. 7. Bland and Altman plots showing the comparison of inter-observer error. (A) Flexion facet centres ($p = 0.000$). (B) Femoro–tibial contact points ($p = 0.025$).

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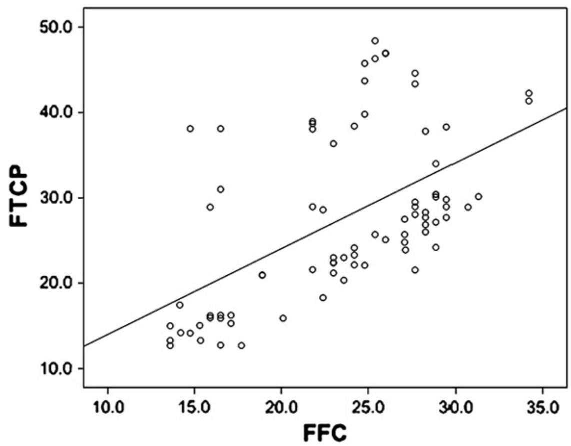

Fig. 8. Scatter graph showing correlation between FFC and FTCP measurements (r = 0.569).

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