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Patellar dislocation is associated with increased tibial but not femoral rotational asymmetry

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Abstract

Purpose Patellar dislocation is associated with a range of anatomical abnormalities affecting the trochlea, extensor mechanism and the tibia. The relationship between patellofemoral instability and rotational abnormalities of the posterior condyles, trochlear groove and proximal tibia has not been adequately determined. This study aimed to identify the frequency and severity of anatomical risk factors to determine their relative contribution to patellofemoral instability.

Methods A retrospective morphological study was undertaken comparing multiple anatomical measurements with magnetic resonance imaging of 50 patients with patellofemoral instability to an age- and gender-matched Control group ($n = 50$). Several techniques were assessed measuring both femoral and tibial axial asymmetry. A new measurement, tibial rotational asymmetry, comparing a line between the midpoints of the collateral ligaments to the axis between the patellar tendon and posterior cruciate ligament, was assessed for its association with patellofemoral instability.

Results Compared to the controls, the patellofemoral instability group demonstrated a significant difference in tibial rotational asymmetry, with a mean of 2.9° (SD 3.2°) externally rotated vs − 1.6° (SD 2.2°) in the control group. Significant differences were also demonstrated regarding the sulcus angle, tibial tubercle–trochlear groove distance, tibial tubercle–posterior cruciate ligament distance, patellar size and the Insall–Salvati ratio. There were no differences between groups regarding the lengths of the posterior condyles, the heights of the trochlear ridges or lateralisation of the trochlear groove. Further analysis of the patellofemoral instability group revealed a subgroup of males with normal anatomy (7/50) and a subgroup of females with isolated patella alta (7/50).

Conclusion Patellofemoral instability is associated with tibial rotational asymmetry due to lateralisation of the tibial tubercle. It is also associated with patella alta and reduced trochlear groove depth. The femoral axial shape is otherwise unchanged.

Level of evidence III.

Keywords Knee · Patella · Patellar dislocation · Patellar instability · Patellofemoral joint · Tibial rotational asymmetry · Femoral rotational asymmetry · Magnetic resonance imaging measurements

Introduction

Patellar dislocation is associated with a range of morphological abnormalities affecting the femur, patella, tibia and soft-tissue structures. Four main factors contribute to patellofemoral instability (PFI): (1) dysplastic trochlear morphology, (2) patella alta, (3) lateralised tibial tubercle and (4) deficient medial patellar soft-tissue stabilisers [4]. Amongst those who experience patellar dislocation, the presence or severity of each of these abnormalities is highly variable. This suggests that bony abnormalities are largely the cause of dislocation in some patients, whereas in other patients, soft-tissue insufficiency, dynamic factors or additional anatomical variations may be implicated [2,

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3]. In patients with high energy injuries and medial soft-tissue disruption, there may be no predisposing anatomical risk factors.

In addition to the well-described abnormalities of patella alta, trochlear dysplasia (TD) and lateralisation of the tibial tubercle, recent research has looked for associated changes in the shape of the tibiofemoral joint [1, 6, 7, 11, 17, 23]. These studies have provided conflicting evidence for whether patients with PFI also have variations in the size and shape of the posterior femoral condyles and tibial plateau. Hypotheses include that differences in the relative lengths of the posterior condyles (PC) and reduced posterior slope of the lateral tibial plateau lead to a greater risk of dislocation [17].

Rotational asymmetry is a concept that defines a divergence between the alignment of the extensor mechanism and the flexion–extension axis of the tibiofemoral joint [15, 21]. It has been described in relation to the femur by comparing the rotational alignment of the trochlear groove relative to the PC. This suggests that, in most femora, the rotational alignment of the PC is not perpendicular to the rotational alignment of the trochlear groove and that this asymmetry is linked to increasing degrees of varus angulation of the proximal tibial joint line [8, 22]. Given the highly variable association between the rotation of the trochlear groove and PC in normal femora [15], it is reasonable to hypothesise that there may be a relationship between PFI and femoral rotational asymmetry (FRA).

Rotational asymmetry in the proximal tibia is indirectly measured using several techniques, including the tibial tubercle–trochlear groove distance (TT–TG) [19], the tibial tubercle–posterior cruciate ligament distance (TT–PCL) [20], and by comparison of the surgical epicondylar axis (SEA) and the rotation of the proximal tibia [12, 18]. Each of these techniques has suggested a relative external rotation of the extensor mechanism in PFI. However, none of them compare it directly to the flexion–extension axis at the level of the tibiofemoral joint. With the use of magnetic resonance imaging (MRI), the medial and lateral collateral ligaments at the level of the tibial plateau can be accurately identified. It is hypothesised that this may be a closer surrogate measure for the axis of rotation of the knee and therefore allow more accurate detection of tibial rotational asymmetry.

Tibial rotational asymmetry (TRA) is defined as a divergence between the alignment of the extensor mechanism and the flexion–extension axis at the level of the tibial plateau. The alignment of the extensor mechanism is measured between the center of the patella tendon anteriorly and the center of the posterior cruciate ligament posteriorly. The flexion–extension axis is measured at the level of the tibial plateau between the center of the lateral collateral ligament and the center of the deep medial collateral ligament. The absence of TRA is defined by an extensor mechanism which is perpendicular to the flexion–extension axis. An externally rotated extensor mechanism relative to the flexion–extension axis is described as a positive value.

The primary aim of this study was to determine the prevalence and severity of FRA and TRA in patients with PFI relative to a Control group. The secondary aims were: (1) to validate a technique for measuring TRA on MRI, (2) document the anatomical risk factors associated with PFI, and (3) to determine the prevalence of patients with PFI and few or no anatomical risk factors.

Materials and methods

This retrospective morphological study was carried out on 100 patients presenting to a single surgeon practice over a 5-year period. As this study was a retrospective analysis of de-identified data, informed consent was not required as part of the ethics approval. Western Health Human Research Ethics Committee approved the study (QA 2015.12). The inclusion criteria for the PFI group ($n = 50$) were patients with a history, clinical examination and MRI findings consistent with a patellar dislocation. The inclusion criteria for the Control group ($n = 50$) were patients presenting to the same surgeon's practice for investigation of knee pain suspected to be due to meniscal pathology in which MRI was obtained. The Control group patients were selected to age-and-gender match the PFI group. Exclusion criteria included diagnosis of other patellofemoral joint pathologies, previous patellofemoral joint surgery, injuries of the anterior cruciate, posterior cruciate or collateral ligaments and previous fractures involving the knee.

All measurements were performed by the senior author. Inter-observer and intra-observer reliability was assessed for all measurements by two independent observers (orthopaedic surgeon and sports medicine doctor) for 10 MRIs at a 1 week interval. The inter-observer and intra-observer reliability of the TRA was performed by three independent observers (orthopaedic surgeon, orthopaedic resident and a sports medicine doctor) for 20 MRIs at a 1 week interval, as the reliability of this measure had not been previously assessed.

MRI analysis: measurement techniques

All measurements were completed using the Osirix proprietary software program (Osirix X MD v. 11.0.3, 64-bit, Pixmeo Sarl, Switzerland). Descriptions of the measurements and their abbreviations are presented in Table 1.

FRA was measured using the Sulcus line (SL) of the trochlear groove relative to the posterior condyles. This involves placing multiple points along the floor of the trochlear groove on successive axial slices. The femur is then orientated using the 3D-multiplanar reconstruction

Table 1 Description of measurements

Femoral and tibial axial measurements	
Epicondylar width (EW)	Distance between the lateral epicondyle and the medial epicondylar sulcus
Posterior condylar angle (PCA)	Angle between the most posterior aspect of the cartilage surface of condyles and the SEA
Surgical epicondylar axis (SEA)	Line from the lateral femoral epicondyle to the sulcus of the medial femoral epicondyle
Femoral rotational asymmetry (FRA)	SL minus the PCA. Positive values indicate that the SL is externally rotated relative to the PCA
Medial posterior condyle length (MPCL)	Measured from the most posterior aspect of the cartilage surface of the medial condyle to the SEA along a line perpendicular to the SEA
Lateral posterior condyle length (LPCL)	Measured from the most posterior aspect of the cartilage surface of the lateral condyle to the SEA, along a line perpendicular to the SEA
Medial trochlear ridge height (MTRH)	Measured from the most anterior aspect of cartilage surface of the medial trochlear ridge to the SEA along a line perpendicular to the SEA
Lateral trochlear ridge height (LTRH)	Measured from the most anterior aspect of the cartilage surface of the lateral trochlear ridge to the SEA, along a line perpendicular to the SEA
Sulcus angle (SA)	Angle between the articular surface of the medial and lateral trochlear facets
Sulcus line (SL)	Points marked along the deepest point of the articular cartilage of the trochlear groove on multiple axial slices. 3D reformatting performed using the 3D-multiplanar reconstruction function to orientate to the coronal alignment of the trochlear groove before measuring the axial alignment of the groove relative to the SEA
Lateralisation of lateral trochlear ridge (LLTR)	Lateralisation of the anterior aspect of the cartilage surface of the lateral trochlear ridge relative to a vertical line from the most posterior aspect of the lateral posterior condyle
Lateralisation of the trochlear groove (LTG)	Lateralisation of the deepest point of the trochlear groove relative to a vertical line from the midpoint between the medial and lateral posterior condyles
Trans-collateral ligament axis (TCA)	Line between the center of the LCL and the center of the deep portion of the MCL (dMCL), measured on the first axial tibial slice completely distal to the articular cartilage
Extensor axis (EA)	Line between the midpoint of the patellar tendon and the center of the posterior cruciate ligament
Tibial tubercle–posterior cruciate ligament distance (TT–PCL)	Mediolateral distance between the midpoint of the insertion of the patellar tendon and the medial border of the posterior cruciate ligament parallel to the dorsal tibial condylar line
Tibial rotational asymmetry (TRA)	Angle formed between the EA and the TCA, measured on the first axial tibial slice completely distal to the articular cartilage. An EA externally rotated relative to the TCA will generate a positive value
PCL lateral-to-midpoint collateral ligaments	Distance from midpoint of the PCL to a line perpendicular to the TCA, extending posteriorly from the midpoint between the LCL and dMCL
PT lateral-to-midpoint collateral ligaments	Distance from the midpoint of the patellar tendon to a line perpendicular to the TCA, extending anteriorly from the midpoint between the LCL and dMCL
Tibial tubercle-medial tibial plateau (MTP) length	Distance on sagittal slice between the TT and MTP
Extensor axis–Posterior tibial condyle angle (EA–PTC)	Angle between the EA and the tangent to the posterior tibial condyles
Extensor axis–transverse tibial axis (EA–TTA)	Angle formed between the EA and a line between the centers of two circles, centered on the cross-section of the medial and lateral tibial plateaus
Tibial tubercle–trochlear groove distance (TT–TG)	The cartilaginous-tendon TT–TG distance was determined between the deepest point of the trochlear groove and the tendon insertion on the tibial tubercle
Extensor axis–SEA angle (EA–SEA)	Angle between the tibial extensor axis and the femoral surgical epicondylar axis, measured by projecting the angles onto the same slice
Patellar measurements	
Insall-Salvati (IS) ratio	Ratio of the length of the patellar tendon to the maximum length of the patella
Patellotrochlear index (PTI)	Overlap percentage of the trochlear cartilage and the articular cartilage of the patella as per described technique

Table 1 (continued)

Patellar measurements	
Patellar length (PL)	On sagittal slice with the longest section of patella
Patellar width (PW)	On axial slice with the widest section of the patella
Patellar tendon length (PTL)	From distal pole of patella to tibial tubercle
Tibial slope measurement	
Anterior slope of the lateral tibial plateau (LTP) relative to MTP	Relative angle of the lateral tibial slope to the medial tibial slope, measured through the center of each plateau. Positive value equals less posterior lateral slope than medial slope

dMCL deep medial collateral ligament; *EA* extensor axis; *LTP* lateral tibial plateau; *MTP* medial tibial plateau; *PCA* posterior condylar angle; *PCL* posterior cruciate ligament; *PT* patellar tendon; *SEA* surgical epicondylar axis; *SL* sulcus line; *TCA* trans-collateral ligament axis; *TT* tibial tubercle; *TT–PCL* tibial tubercle–posterior cruciate ligament distance; *TT–TG* tibial tubercle–trochlear groove distance

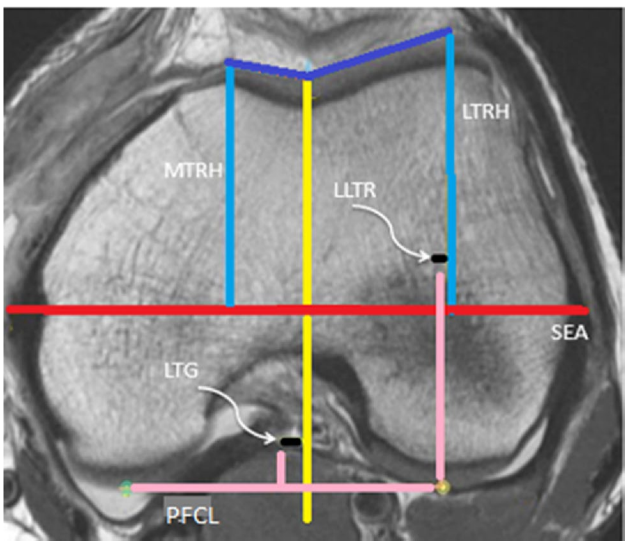

Fig. 1 MRI axial slice: femoral axial measurements. LLTR, lateralisation of the lateral trochlear ridge; LTG, lateralisation of the trochlear groove; LTRH, lateral trochlear ridge height; MTRH, medial trochlear ridge height; PFCL, posterior femoral condylar line; SEA, surgical epicondylar axis

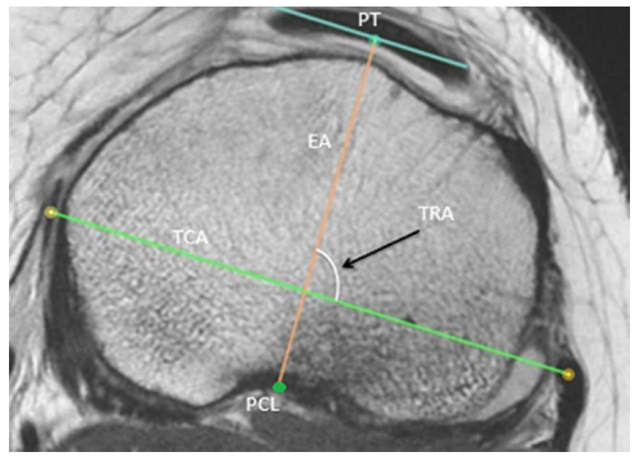

Fig. 2 Tibial rotational asymmetry (TRA) measurement. The TRA (angle indicated by black arrow) is the angle between the EA (orange line) and the TCA (green line), measured on the first axial tibial slice completely distal to the articular cartilage. Blue dot—midpoint of PT; yellow dots—dMCL and LCL; green dot—center of the PCL. EA, extensor axis; PCL, posterior cruciate ligament; PT, patellar tendon; TCA, trans-collateral ligament axis; TRA, tibial rotational asymmetry

(MPR) function to align with the coronal alignment of the SL. The angle between the SL and the surgical epicondylar axis (SEA) is then measured while maintaining this coronal orientation.

The axial measurements of the femur were performed on the axial slice which most clearly identified the SEA (Fig. 1). This slice was used to determine the epicondylar width (EW), posterior condylar angle (PCA), SL, medial posterior condylar length, lateral posterior condylar length, medial trochlear ridge height, lateral trochlear ridge height, sulcus angle (SA), lateralisation of the lateral trochlear ridge and lateralisation of the trochlear groove.

TRA was measured on the first axial slice showing a complete cross-section of bone below the articular surface (Fig. 2). A line was drawn from the center of the width of the patellar tendon to the center of the posterior cruciate ligament (PCL). A second line was drawn between the center of the lateral collateral ligament (LCL) and the center of the deep portion of the medial collateral ligament (dMCL). Where there was uncertainty in identifying any of the ligaments on a single slice, the ligament was traced from proximal to distal attachments along multiple slices. Identifying the center of the dMCL often required reference to multiple slices, starting at the femoral insertion and moving distally. Care was taken to exclude the thinner posterior oblique section of the MCL and only measure the center point of the condensation of the dMCL. The MCL and LCL were able to be identified in all 100 MRIs. The angle between the extensor axis (EA) and the trans-collateral ligament axis (TCA) was measured and a positive value recorded when the EA was externally rotated relative to a line perpendicular to the TCA.

The first tibial slice completely distal to the articular cartilage was also used to determine the EA-to-posterior tibial condyle angle, the TT–PCL distance and the EA-to-transverse tibial axis angle (Fig. 3). The lateral and medial tibial slopes were measured relative to one another. Measurement of the true tibial slope relative to the length of the tibia was not possible due to only a short segment of tibia being available on MRI.

TD was classified for all 100 cases by the senior author using the Dejour classification as per the MRI technique described by Nelitz et al. [13, 14, 25] (Table 2). Cases with no TD, including an SA < 145°, were classified as Dejour grade zero.

The PFI group was assessed for the presence or absence of several anatomical risk factors. For this study, risk factors were classified as: SA > 145°; TRA ≥ 0°; TT–TG > 16 mm; Insall–Salvati (IS) ratio > 1.3 [5] and severe dysplasia (Dejour classification of B/C/D).

Statistical analysis

Sample size was calculated considering an a priori power calculation using a three-degree difference in TRA as a minimum clinically important difference. A minimum sample size of 50 in each group had a 95% chance of detecting such a difference, with an alpha level of 0.05. Inter-observer and intra-observer reliability were calculated using the intra-class correlation coefficient. The data are reported as means ± standard deviations (SD). An independent Student's *t* test was used to compare the PFI group with the Control group. For all analyses, $p < 0.05$ was considered to indicate statistical significance. Prevalence data were reported descriptively using numbers and percentages (95% CI). Pearson's Chi-square and Fisher's exact test were used to test association between categorical variables as appropriate. Binary logistic regression was used to identify the measurements that were predictive of dislocation. Variables were included in the model if univariate analysis found a significant relationship between each variable and dislocation ($p < 0.05$). All analyses were conducted using SPSS v.27.0.

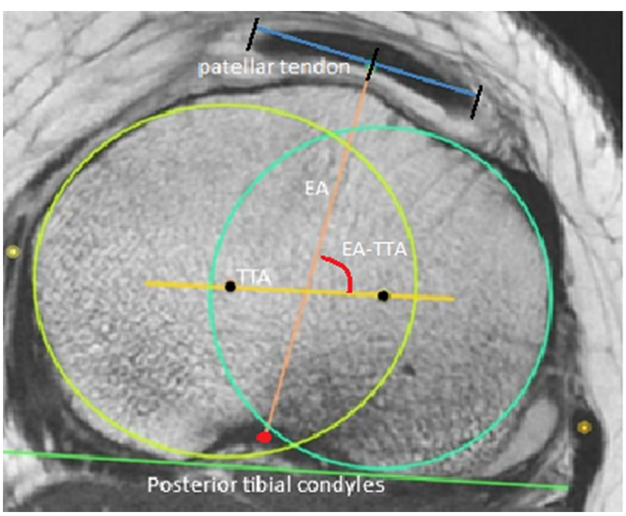

Fig. 3 The extensor axis–transverse tibial axis (EA–TTA) measurement. The EA–TTA is an angle (red line) formed between the EA (orange line) and a line between the centers of two circles (yellow line), centered (black dots) on the cross-section of the medial and lateral tibial plateaus (blue and yellow circles). Blue dot—midpoint of PT; Yellow dots—dMCL and LCL; Red dot—center of the PCL. EA, extensor axis; TTA, transverse tibial axis

Table 2 Distribution of trochlear dysplasia types in PFI and control group Dejour

Dejour classification	PFI group	Control group
Zero	12 (24%)	40 (80%)
A	15 (30%)	10 (20%)
B	16 (32%)	0 (0%)
C	2 (4%)	0 (0%)
D	5 (10%)	0 (0%)

PFI patellofemoral instability

Results

The intra-class correlation coefficients were excellent for all measurements. The inter-observer reliability for the TRA ranged from 0.86 to 0.91 and the intra-observer reliability from 0.86 to 0.94 for the three observers.

The demographic and diagnostic data from the PFI and Control groups are presented in Table 3. As there was no difference in the mean femoral width between the PFI and Control groups, distances are presented in mm, rather than ratios.

Results related to the axial shape of the femur are presented in Table 4. There was no difference in the FRA between the PFI and Control groups. There was a

Table 3 Subject demographics

	PFI group	Control group	*p* value[a]
Mean age at MRI, years	20.4	22.7	n.s
Sex, male: female	28:22	29:21	n.s
Side, right: left	27:23	28:22	n.s

MRI magnetic resonance imaging; *PFI* patellofemoral instability; *n.s.* not statistically significant

[a]Independent Student's *t* test was performed to compare the PFI group with the control group

Table 4 Comparison of measurement results between the PFI and control groups

Femoral measurements	PFI group		Control group		
	Mean	SD	Mean	SD	*p* value[a]
EW* (mm)	80.3	7.3	80.3	6.8	n.s
Femoral AP height to EW* (mm)	0.8	0.5	0.8	0.5	n.s
PCA (°)	− 2.1	2.0	− 2.4	1.7	n.s
FRA (°)	*− 2.1*	*3.5*	*− 1.9*	*2.8*	n.s
MPCL (mm)	24.4	2.3	24.4	2.4	n.s
LPCL (mm)	23.4	2.3	22.9	2.5	n.s
MTRH (mm)	35.9	3.1	36.0	3.4	n.s
LTRH (mm)	39.4	3.8	39.7	3.7	n.s
SA (°)	154.8	11.4	137.9	8.1	< 0.0001
LLTR (mm)	− 1.5	2.4	− 2.2	2.4	n.s
LTG (mm)	0.8	2.4	1.1	2.3	n.s
SL to SEA (°)	0.0	3.4	− 0.5	2.8	n.s
Patellar/epicondylar ratio*(mm)	0.5	0.0	0.5	0.0	< 0.0001
PL (mm)	39.2	5.1	42.3	3.6	< 0.0001
PW (mm)	40.3	5.0	42.7	3.9	0.01
PTI	0.4	0.2	0.4	0.1	n.s
Tibial measurements					
TT–PCL distance (mm)	22.6	3.8	20.6	3.6	0.01
TRA (°)	*2.9*	*3.2*	*− 1.6*	*2.2*	*< 0.0001*
PCL lateral-to-midpoint collateral ligaments (mm)	− 0.7	1.9	− 0.1	1.6	n.s
PT lateral-to-midpoint collateral ligaments (mm)	1.7	3.1	− 1.9	2.1	< 0.0001
TT-to-MTP length (mm)	29.4	4.0	28.8	3.5	n.s
EA–PTC (°)	14.9	3.3	13.9	2.9	n.s
EA–TTA (°)	11.8	3.9	10.6	3.8	n.s
Increase in anterior slope of LTP relative to MTP (°)	2.5	3.1	− 0.3	2.7	< 0.0001
Other measurements					
TT–TG (mm)	15.5	5.3	11.2	4.0	< 0.0001
EA–SEA (°)	12.6	5.2	6.7	4.0	< 0.0001
IS ratio	1.5	0.3	1.2	0.2	< 0.0001
PTL (mm)	58.3	7.5	51.7	6.8	< 0.0001

EA–PTC extensor axis to posterior tibial condyles; *EA–SEA* extensor axis to surgical epicondylar axis; *EA–TTA* extensor axis to transverse tibial axis; *EW* epicondylar width; *FRA* femoral rotational asymmetry; *IS* Insall–Salvati; *LLTR* lateralisation of the lateral trochlear ridge; *LPCL* lateral posterior condylar length; *LTG* lateralisation of the trochlear groove; *LTP* lateral tibial plateau; *LTRH* lateral trochlear ridge height; *MPCL* medial posterior condylar length; *MTP* medial tibial plateau; *MTRH* medial trochlear ridge height; *n.s.* not statistically significant; *PCA* posterior condylar angle; *PCL* posterior cruciate ligament; *PFI* patellofemoral instability; *PL* patellar length; *PT* patellar tendon; *PTI* patellotrochlear index; *PTL* patellar tendon length; *PW* patellar width; *SA* sulcus angle; *SD* standard deviation; *SEA* surgical epicondylar axis; *SL* sulcus line; *TRA* tibial rotational asymmetry; *TT* tibial tubercle; *TT–PCL* tibial tubercle–posterior cruciate ligament distance; *TT–TG* tibial tubercle–trochlear groove distance

*Because the average femoral width in the PFI and Control groups were identical, length measurements are presented in millimetres, rather than as a ratio

[a]Independent Student's *t* test was performed to compare the PFI group with the Control group

significant difference in the SA ($p < 0.0001$) with a mean angle in the PFI group of 154.8 vs 137.9° in the Control group. There was no significant difference between the PFI and Control groups for the other axial femoral measurements.

Data describing the axial alignment of the tibia and extensor mechanism are also presented in Table 4. There was a statistically significant difference in the TRA, with a mean of 2.9° (SD 3.2°) externally rotated in the PFI group compared to − 1.6° (SD 2.2°) in the Control group ($p < 0.0001$). In the

PFI group, 44 of 50 patients (88%) had a TRA ≥ 0°, while in the Control group, 41 of 50 patients (82%) had a TRA < 0°.

Other measures of tibial deformity found to be statistically significant were the TT–PCL and the TT–TG. The TT–PCL had a mean of 22.6 mm (SD 3.8) in the PFI group and 20.6 mm (SD 3.6) in the Control group ($p = 0.01$). In the PFI group, 19 of 50 patients (38%) had a TT–PCL ≥ 24 mm, and in the Control group, 42 of 50 patients (84%) had a TT–PCL < 24 mm. The TT–TG had a mean of 15.5 mm (SD 5.3) in the PFI group and 11.2 mm (SD 4.0) in the Control group ($p < 0.0001$). In the PFI group, 21 of 50 patients (42%) had a TT–TG > 16 mm, and in the Control group, 43 of 50 patients (86%) had a TT–TG ≤ 16 mm. Univariate binary logistic regression identified that all three measures (TRA, TT–PCL, and TT–TG) were significantly associated with dislocation, with the strongest association between TRA and PFI. Tests of collinearity were conducted and the variance inflation factor (VIF) across all variables was < 3; thus, all measures were included in the final model. The final model found that TRA was the only significant predictor of dislocation ($p < 0.001$) with an adjusted odds ratio of 1.95 (Table 5).

The difference between the medial and lateral tibial slope was significantly greater in the PFI group {mean [SD] 2.5° [3.1°] reduced posterior lateral tibial slope, compared to medial} than the Control group {− 0.3° [2.7°]; $p < 0.0001$}.

Regarding the extensor mechanism, compared to the Control group, there was a significant increase in the IS ratio {mean [SD] 1.5 [0.3] vs 1.2 [0.2]; $p < 0.0001$} and patellar tendon length {58.3 [7.5] vs 51.7 [6.8] mm; $p < 0.0001$} in the PFI group. There was also a decrease in the patellar length {39.2 [5.1] vs 42.3 [3.6] mm; $p < 0.0001$} and patellar width {40.3 [5.0] vs 42.7 [3.9] mm; $p = 0.01$} in the PFI group compared to the Control group. There were no significant differences in the PTI or the distance from the tibial plateau to the tibial tubercle between the groups.

A subgroup of 23 patients with severe TD (Dejour B, C, or D) and PFI was identified. Additional analysis compared the femoral measurements in this subgroup with the Control group. There was a significant difference in the SA between patients with severe TD and the Control group {mean [SD] 162° [11.6°] vs 138° [8.1°]; $p < 0.0001$}. The remaining measures of femoral axial shape were not statistically significant (Table 6).

Furthermore, to determine the prevalence of patients with few or no anatomical risk factors, analysis of the 50 PFI patients was conducted. This identified that 36 of 50 (72%) PFI patients had multiple anatomical risk factors. Of the remaining 14 cases, 7 had no risk factors and 7 had only patella alta with Dejour classification zero or A TD. All 7 cases with no anatomical risk factors were male and all 7 with isolated patella alta were female.

Table 6 Comparison of femoral measurements between severe trochlear dysplasia (Dejour B, C, and D) and Controls

	Severe dysplasia group ($N = 23$)		Control group ($N = 50$)		
	Mean	SD	Mean	SD	p value[a]
EW* (mm)	81.9	7.7	80.3	6.8	n.s
PCA (°)	-1.9	1.9	-2.4	1.7	n.s
FRA (°)	*-1.9*	*3.7*	*-1.9*	*2.8*	n.s
MPCL (mm)	24.5	2.3	24.4	2.4	n.s
LPCL (mm)	23.8	2.5	22.9	2.5	n.s
MTRH (mm)	36.7	2.8	36.0	3.4	n.s
LTRH (mm)	40.5	3.6	39.7	3.7	n.s
SA (°)	162.2	11.6	137.9	8.1	< 0.0001
LTG (mm)	1.3	2.4	1.1	2.3	n.s
SL to SEA (°)	0.1	3.9	-0.5	2.8	n.s

*Because the average femoral width in the PFI and Control groups were identical, length measurements are presented in millimetres, rather than as a ratio

a = Independent Student's *t* test was performed to compare the PFI group with the Control group

EW, epicondylar width; FRA, femoral rotational asymmetry; LPCL, lateral posterior condylar length; LTG, lateralisation of the trochlear groove; LTRH, lateral trochlear ridge height; MPCL, medial posterior condylar length; MTRH, medial trochlear ridge height; n.s., not statistically significant; PCA, posterior condylar angle; SA, sulcus angle; SD, standard deviation; SEA, surgical epicondylar axis; SL, sulcus line

Table 5 Univariate and multivariate binary logistic regression analysis of the TRA, TT–PCL, and TT–TG

	Univariate			Multivariate		
	Unadjusted OR	95% CI	p value	Adjusted OR	95% CI	p value
TRA	2.01	1.53–2.64	< 0.001	1.95	1.46–2.59	< 0.001
TT–PCL	1.17	1.04–1.31	0.009	0.98	0.84–1.14	n.s
TT–TG	1.22	1.10–1.35	< 0.001	1.13	0.99–1.29	n.s

CI confidence intervals; *n.s.* not statistically significant; *OR* odds ratio; *TRA* tibial rotational asymmetry; *TT–PCL* tibial tubercle–posterior cruciate ligament distance; *TT–TG* tibial tubercle–trochlear groove distance

Discussion

The most important finding of the present study was TRA was common in patients with PFI due to lateralisation of the tibial tubercle. In contrast, FRA due to either change in the rotational alignment of the trochlear groove or the relative lengths of the posterior condyles was not identified. The only significant difference in the axial shape of the femur between the two groups was an increase in the SA in the PFI group.

Our TRA measurement technique was found to be reproducible with very good inter-observer and intra-observer reliability. Based on the data from this study, a TRA angle of $\geq 0°$ is considered to be abnormal.

In comparison to other measures of tibial asymmetry (TT–PCL and TT–TG) and PFI, the TRA had a higher positive predictive value (PPV). The TRA was found to have a PPV of 88% compared to the TT–PCL with a PPV of 38%. Of note, the initial paper on the TT–PCL also reported a PPV of 38% [20]. This study recorded a PPV of 42% for the TT–TG. Further regression analysis determined that TRA had a stronger association with PFI than either TT–PCL or TT–TG.

The combination of these findings suggests that the TRA may be a more sensitive and clinically relevant technique than either of the existing techniques. There are several possible reasons for this. First, the TRA is an angle rather than a measurement of distance; therefore, it is not affected by variations in a patient's overall size. Second, it is measured at a single level unlike the TT–TG which relies on extrapolation of the position of the tubercle several centimetres proximally onto the trochlear groove. Third, it relies on the position of the collateral ligaments at the level of the joint line, which is likely to be a more clinically relevant transverse landmark than the posterior tibial cortex used in the measurement of the TT–PCL.

TRA can be caused by relative changes in any of the four points on the axes, namely the collateral ligaments, PCL and patellar tendon [9, 10]. The assumption is that in PFI, it is largely due to lateralisation of the patellar tendon. It has been suggested that the position of the PCL changes in PFI [16, 20]. This can be assessed by measuring the offset of the PCL and the patellar tendon relative to the midpoint of the TCA. In this study, there was no difference in the relative position of the PCL between individuals in the PFI group compared to the Control group. The cause of TRA in PFI seems to be largely due to lateralisation of the tibial tubercle.

This study found no difference in the length of the posterior condyles between the PFI and Control groups. Two previous studies have found small differences in the lengths of the PC in patients with PFI. Roger et al. found an association between TD and the PCA, noting a relatively shorter lateral posterior femoral condyle in patients with PFI compared to controls [17]. Liu et al. similarly reported that the lateral posterior femoral condyle was almost 3 mm shorter, on average, in patients with PFI [11]. However, Van Haver et al. found no difference in the PCA between the group of patients with TD and the Control group [26]. In the current study, no differences were detected in the PCL and lengths of the condyles between the PFI and Control groups.

There may be several explanations for these differences, including variation in the study populations. In the current study, the Control group predominantly comprised of patients with meniscal pathology, while in the study by Roger et al. the Control group primarily had anterior cruciate ligament injuries.

Subgroup analysis of the PFI group was performed to identify patients with limited anatomical risk factors. A limitation of the subgroup analysis is the selection of normal values. In this study, we selected a TT–TG over 16 mm and an IS ratio over 1.3 as abnormal based on our interpretation of the literature. Other studies have used TT–TG > 20 mm and IS ratios of either 1.2 or 1.5 as the cut-offs [24, 27].

Applying the selected normal values, we identified two distinct phenotypes with limited anatomical risk factors. The first group had none of the anatomical risk factors for dislocation, were all male, and were injured during contact sports. The suggestion is that this group may have disrupted their medial retinacular structures, including the medial patellofemoral ligament, during high energy activities. The second group had patella alta and mild or absent TD as the only anatomical risk factors. In contrast to the first group, these patients were all female. Identification of subgroups may help to guide surgical decision-making regarding the selection of medial patellofemoral ligament reconstruction, patellar distalisation or translation procedures and trochleoplasty. Further clarification of these subgroups and the clinical relevance is required.

The data from this study suggest that in most patients with PFI, bony abnormalities are concentrated in the tibia and the extensor mechanism, rather than in the femur. The only femoral change was flattening of the trochlear groove. This raises the possibility that trochlear groove changes may be secondary in some patients. The underlying deformity may be in the anterolateral tibia and the patellar tendon insertion rather than a combination of abnormalities affecting both bones. There may be separate subgroups in which very severe TD, or a shortened lateral posterior condyle may be the dominant factors contributing to instability; however, these groups were not identified in this study.

The higher positive predictive value of the TRA relative to other measures of tibial tubercle lateralisation may allow it to be incorporated into treatment algorithms to determine appropriate surgical management of PFI. Patients with instability but a normal TRA may be more confidently treated with a proximal MPFL reconstruction rather than a distal realignment or a combined operation.

This study has limitations. The TRA measurement technique requires careful identification of somewhat indistinct soft-tissue landmarks, which can lead to measurement errors. However, the very high inter-observer and intra-observer reliability in this study suggests that the TRA measurement technique can be reliably used regardless of the clinician's level of experience. Another limitation was the inability to assess the long-leg alignment of the knees in MRI. As the imaging available did not extend the full length of the tibia, instead of measuring the tibial slope, the relative slope of the medial and lateral compartments was measured.

Conclusion

PFI is associated with tibial rotational asymmetry due to lateralisation of the tibial tubercle. Additionally, reduced posterior slope of the lateral tibial plateau, patella alta and decreased sulcus angle are independently associated with patellar dislocation. PFI is not associated with changes in the axial shape of the femur.

Author contributions LG designed the study, collected data, and wrote the manuscript. RJ collected data and wrote the manuscript. PW collected data and wrote the manuscript. TC designed the study and wrote the manuscript. ST designed the study, collected data, and wrote the manuscript. All authors read and approved the final manuscript.

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Declarations

Conflict of interest None applicable.

Ethical approval We have approval to complete this study from our Institutional Review Board—the Western Health Research and Governance Administration with the following Reference number—QA 2015.12.

Informed consent As the study was a retrospective analysis of de-identified data, informed consent was not required as part of the ethics approval.

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