The Knee 26 (2019) 435–443

Contents lists available at ScienceDirect

The Knee

Coronal tibial alignment is linked to femoral rotational asymmetry: Implications for total knee arthroplasty surgery

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ARTICLE INFO

Article history:
Received 22 January 2018
Received in revised form 1 December 2018
Accepted 8 January 2019

Keywords:
Knee
Arthroplasty
Total knee replacement
Femoral rotation
Epicondylar axis
Femoral rotational asymmetry

ABSTRACT

Background: Femoral rotational asymmetry (FRA) is the difference in rotational alignment between the trochlear groove and posterior condyles. We hypothesize that FRA increases as the tibial plateau becomes more varus due to internal rotation of the posterior condyles and external rotation of the trochlear groove to ensure a vertical trochlear groove at 90º knee flexion.
Methods: Seventy lower limb Computed Tomography (CT) scans were reviewed by two examiners. Comparisons were made between both the sulcus line (SL) and posterior condylar line (PCL) relative to the surgical epicondylar axis (SEA). Femoral and tibial coronal alignment were measured on CT scanograms and 3D reconstructions. Correlation analysis was performed to identify associations between FRA, SL and PCL and the coronal alignment of the tibia and femur.
Results: The mean FRA was +2.9° (SL externally rotated to PCL) (−2.4° to +7.7°, SD 2.2°). FRA greater than four degrees occurred in (17/70) 24% of knees. A statistically significant correlation was found between the degree of FRA and proximal tibial varus (MPTA) ($R2 = 0.67$, $p < 0.001$). Furthermore, there were significant correlations between the SL and the MPTA ($p < 0.001$, $R^2 = 0.77$) and the PCL and the MPTA ($p < 0.001$, $R^2 = -0.41$).
Conclusion: Native femora are frequently rotationally asymmetrical. As the tibial plateau becomes increasingly varus there is an increase in external rotation of the SL and internal rotation of the PCL. The effect is to maintain a more vertical trochlear groove during flexion in the presence of a varus tibia.

1. Introduction

Measured resection is a popular technique utilized to establish implant alignment and soft tissue balance in total knee arthroplasty surgery [1,2]. It relies on anatomical landmarks including the Posterior Condylar Line (PCL), the Surgical Epicondylar Axis (SEA) and the anteroposterior axis (APA) to determine the rotational alignment of the femoral component [3,4]. The PCL is a line drawn across the surface of the posterior femoral condyles. The SEA is a line intersecting the lateral epicondyle and the

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https://doi.org/10.1016/j.knee.2019.01.008
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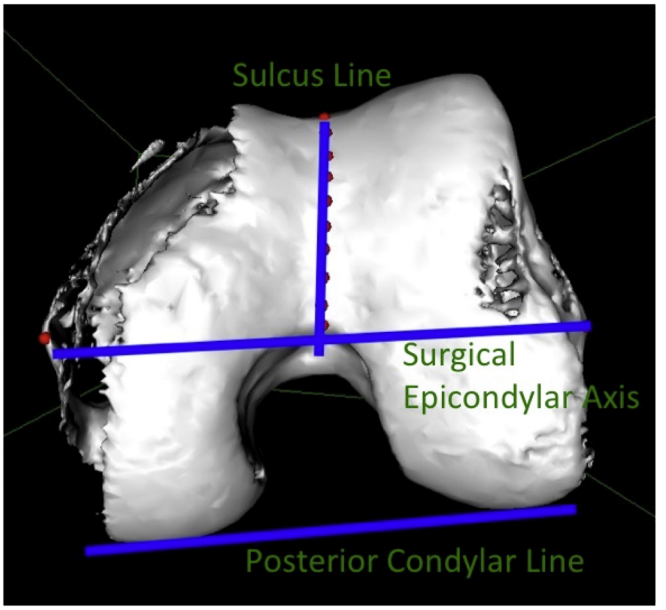

Figure 1. Screenshot of distal femur including ROI points for sulcus line, medial epicondylar sulcus and lateral epicondyle.

medial epicondylar sulcus (Figure 1) and has been described as being perpendicular to the functional flexion extension axis (FEA) of the knee and the axis of rotation of the patella [5–7]. The SEA is used for research purposes as it is identifiable on postoperative Computed Tomography (CT) scans, therefore gives an indication of surgical accuracy [8,9]. The SEA can be difficult to accurately identify intraoperatively so more easily identifiable landmarks such as the PCL are normally used [10,11]. When performing mechanical axis alignment three degrees of external rotation is added to the PCL to compensate for the average three degrees of varus in the tibial plateau. Kinematic Alignment requires a resection parallel to the PCL. There is considerable anatomical variation between the SEA and posterior condyles therefore both of these techniques will lead to a range of femoral component rotation relative to the SEA [12–16].

The rotational alignment of the trochlear groove can also be referenced to determine femoral component rotation. The APA, also known as Whiteside's Line (WL) is used to determine the rotational alignment of the trochlear groove [6,17]. It is formed by a line between two points, the deepest part of the trochlear groove anteriorly and the centre of the intercondylar notch posteriorly. Measurement of this line is unreliable and this stems from utilizing a two-dimensional (2D) line to measure a three-dimensional (3D) curve [6]. A more accurate 3D technique known as the sulcus line (SL) was developed correcting for variations in the coronal alignment of the curve of the trochlear groove to isolate its rotational alignment [17,18].

The anatomical variation between the rotational alignment of the trochlear groove and posterior condyles can be described as femoral rotational asymmetry (FRA) [19]. A large series of CT scans in knees without osteoarthritis confirmed that FRA was not caused by arthritic bone loss and proposed a classification system [20].

The hypothesis of this study is that increasing tibial varus is linked to increasing FRA due to increasing internal rotation of the PCL relative to the SEA and increasing external rotation of the SL relative to the SEA. The suggestion is that this is a compensatory anatomical variation which occurs in order to keep the trochlear groove vertical and the patella centred over the knee and ankle when the knee is flexed to 90° (Figure 2a, b, c, d).

2. Methods

2.1. Study design

A retrospective case series study of lower limb CT scans.

2.2. Patients

Eighty two preoperative CT scans for patients undergoing total knee arthroplasty (TKA) between 2012 and 2016 for osteoarthritis was performed. All scans were performed using the Perth protocol with 1.25 mm slices including the hip, knee and ankle (GE Optima 660 Brightspeed, 128 slice scanner). The data was imported into the Osirix (Osirix v 5.6 64-bit, Pixmeo Sarl, Switzerland) proprietary software program.

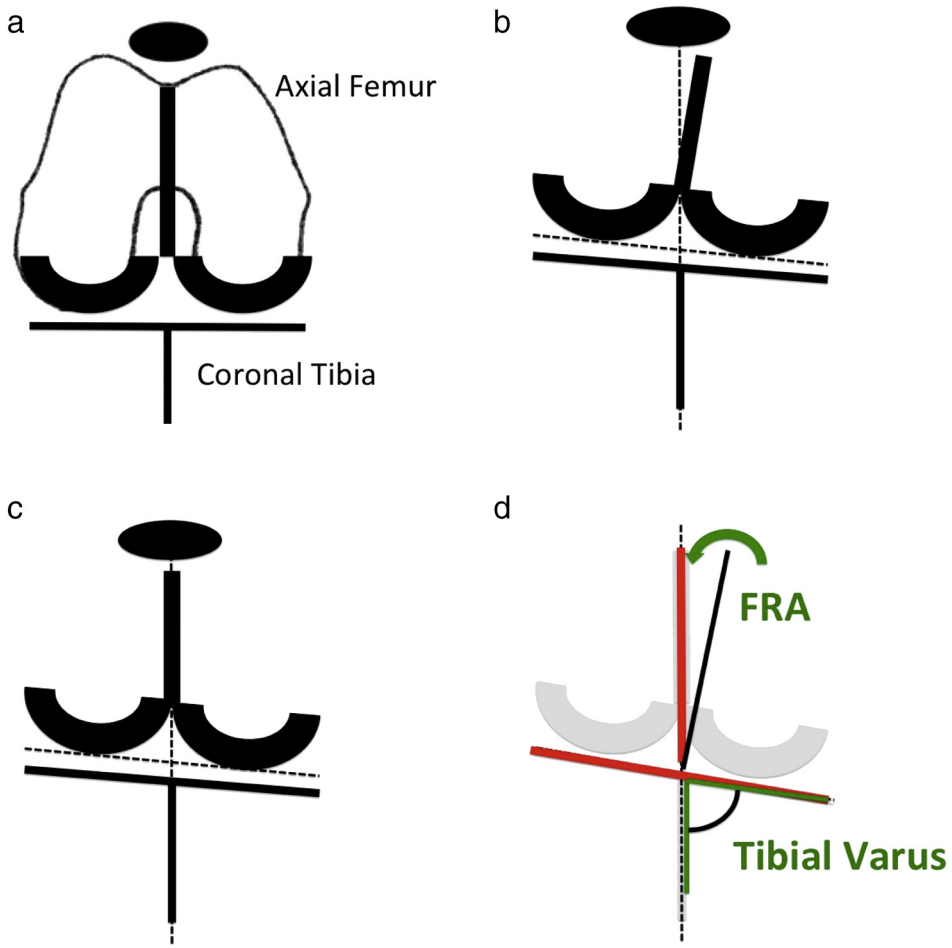

Figure 2. a, b, c, d. Femoral asymmetry linked to proximal tibial varus. Diagrams are of an axial view of the distal femur and a coronal view of the tibia with the posterior condyles sitting on the tibial plateau. a — a symmetrical distal femur sitting on a perpendicular (MPTA = 0°) tibial plateau. b — a symmetrical distal femur sitting on a varus (MPTA > 0°) plateau. c — an asymmetrical distal femur rotating the trochlear groove back under the patella to compensate for a varus (MPTA > 0°) plateau. d — the angles of femoral rotational asymmetry (FRA) and tibial varus (MPTA).

2.3. Anatomical landmarks and reference planes

Lateral epicondyle, medial epicondylar sulcus and posterior condyles were initially referenced on 2D axial CT slices and marked with region of interest (ROI) points. A volume rendering 3D reconstruction was performed with bone subtraction techniques used to remove the patella and tibia. A 3D surface rendering was then performed allowing the medial and lateral epicondyles and the medial epicondylar sulcus to be viewed in multiple planes to confirm their location. The deepest points in the trochlear groove were marked with eight to 12 ROI points on the surface rendering. The 3D reconstruction was rotated in the coronal plane to find the coronal direction which was looking directly along the coronal line of the trochlear groove. A screenshot was taken which included the SL and the ROI points marking the lateral epicondyle and medial epicondylar sulcus. The image was imported into Adobe Photoshop (Adobe Photoshop CC v.5.0 64-bit, released 2015, Adobe Systems Incorporated). The SL was measured in relation to the SEA and PCL utilizing the angle tool utilizing a method validated by Watanabe [21,22]. Angles were measured by two blinded examiners. In ten cases the ROI points and measurements were completed by each examiner to assess inter-observer reliability.

Coronal plane CT Scanogram images was utilized to measure distal femoral condylar angle (DFCA) and Medial Proximal Tibial Angle (MPTA). The DFCA was defined as the angle between the mechanical axis of the femur and distal femoral condylar line. The MPTA was defined as the angle between the mechanical axis of the tibia and a line across the proximal tibial plateau [19]. Cases with severe erosive osteoarthritis in which the landmarks for the SEA or the pre-arthritic contour of the distal femoral condyles or tibial plateau could not be identified were excluded.

Calculations were produced by combining the SL and PCL in order to assess how closely each technique would recreate the SEA. The number of outliers greater than three degrees from the SEA was calculated for each technique. The techniques chosen were; i) SL alone, ii) PCL alone, iii) PCL + 3°, iv) PCL + the mean difference between the PCL and SEA, v) the average of the SL and the PCL + 3° and vi) the average of the SL and the "PCL + the mean difference between the PCL and the SEA".

Table 1
Comparison of the rotational landmarks in 78 knees.

	Mean	SD	Range	Outliers more than 3° from SEA, n = 78 (percent)
SL	+0.3°	2.2°	−4.9° to +4.9°	11 (14%)
PCL	−2.4°	1.7°	−6.5° to +0.9°	31 (40%)
FRA	2.8°	2.2°	−2.8 to +8.3°	NA
PCL + 3°	+0.6°	1.7°	−3.5° to +3.9°	9 (12%)
PCL + 2.4°	0.0°	1.7°	−4.1° to +3.3°	4 (5%)
Average SL and PC + 3°	+0.4°	1.6°	−3.2° to +3.9°	3 (4%)
Average SL and PCL + 2.4°	+0.1°	1.6°	−3.5° to +3.6°	4 (5%)

Table 2
Comparison of rotational and coronal landmarks in 70 knees without severe tibial bone loss.

	Mean	SD	Range
SL to SEA (degrees)	+0.5°	2.1°	−4.5° to +4.3°
PCL to SEA (degrees)	−2.4°	1.5°	−5.9° to +0.9°
FRA (SL to PCL)	2.9°	2.2°	−2.4° to +7.7°
DFCA to mechanical axis (degrees valgus)	+3.4°	2.3°	−1.8° to +9.7°
MPTA (degrees varus)	+3.3°	1.9°	−1.5° to +7.4°

2.4. Statistical analysis

Analyses to determine Intraclass Correlation Coefficient (ICC), means, SD, and ranges were conducted. T-tests and one-way ANOVA and Pearson's correlations were applied to compare groups. Significance was set at the $p < 0.05$ level. SPSS v.16.0 was used for all analyses.

2.5. Power analysis

A pre-hoc power analysis for an alpha level of 0.05 and an effect size of 0.5 was 64 cases.

2.6. Ethical approval

Ethics approval was gained from Western Health Low Risk Ethics Panel (QA2017.35).

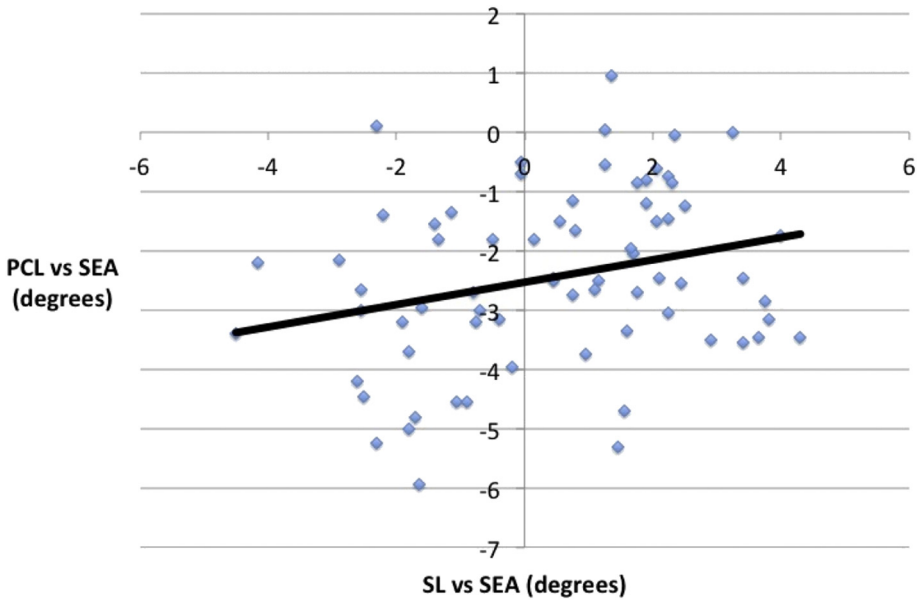

Figure 3. Scatter graph comparing the angles of the SL and PCL relative to the SEA.

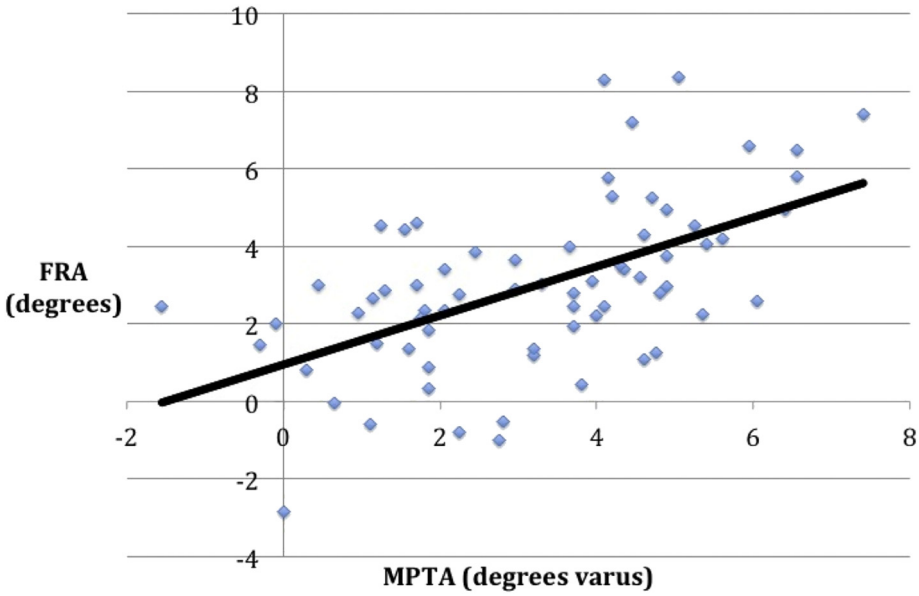

Figure 4. Scatter graph displaying a linear relationship between the degree of proximal tibial varus and degree of FRA.

3. Results

Four of the 82 CT scans were excluded due to difficulty identifying the epicondylar axis leaving 78 cases (Table 1). In a further eight cases tibial bone loss due to osteoarthritis made it difficult to determine the alignment of the pre-arthritic tibial plateau leaving 70 cases to be analyzed (Table 2). There was no significant difference of means or variance between the rotational landmarks in the group in which the MPTA could be measured and the group in which it was obscured by arthritic bone loss.

There was a wide range of individual variation between the rotational alignment of the SL and the PCL (Figure 3).

There were significant correlations between the degree of FRA and the degree of proximal tibial varus (MPTA). (Figure 4) ($p < 0.001$, $R^2 = 0.67$). There were also significant correlations between the SL and the MPTA ($p < 0.001$, $R^2 = 0.77$), (Figure 5) and the PCL and the MPTA ($p < 0.001$, $R^2 = -0.41$), (Figure 6). Increasing proximal tibial varus was linked to both increasing external rotation of the trochlear groove and internal rotation of the posterior condyles, relative to the SEA. There

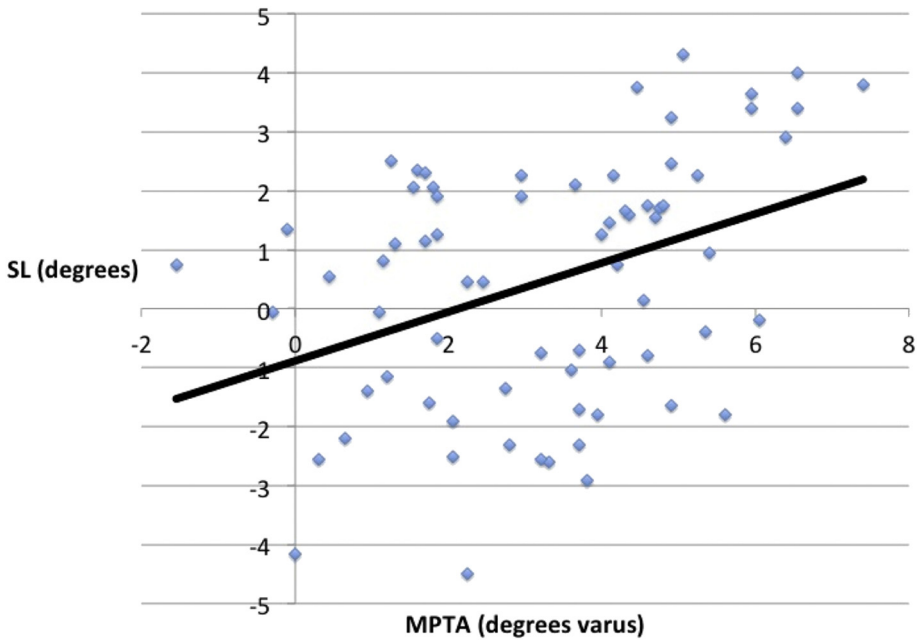

Figure 5. Scatter graph showing a correlation between the SL and proximal tibial varus.

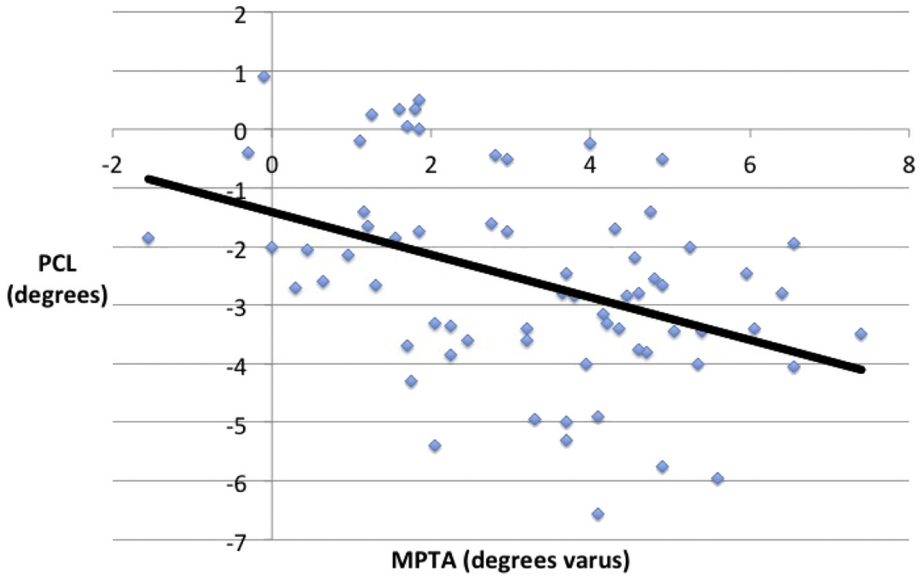

Figure 6. Scatter graph displaying a correlation between the PCL and proximal tibial varus.

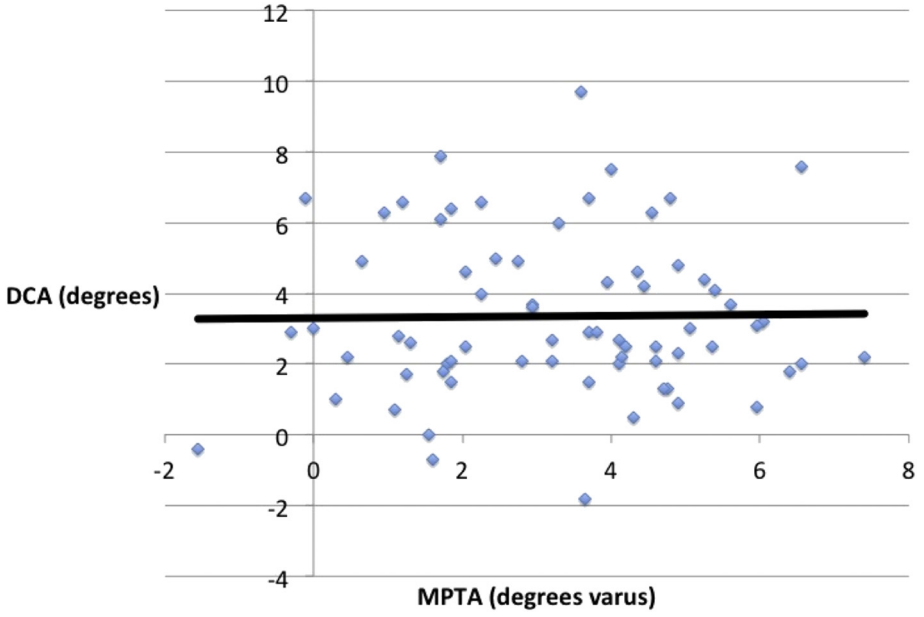

Figure 7. Scatter graph depicting no correlation between the coronal alignment of the distal femur and the rotational alignment of the distal femur.

Table 3
Three techniques and the amount they change the rotation of the trochlear groove between the native trochlear groove and the femoral component's trochlear groove (70 knees without severe bone loss).

	Mean (Positive value ER groove compared to native position)	SD	Range	Outliers which change the rotation of the groove by more than 3° (%)
PCL +3°	+0.1	2.2°	−4.8° to +5.4°	19%
Average SL and PCL + 3°	0°	1.1°	−2.4° to +2.7°	0%
PCL	−2.9°	2.2°	−7.8° to +2.4°	47%

was no correlation between the coronal alignment of the distal femur and the rotational alignment of the distal femur (Figure 7). There was no correlation between the DFCA and MPTA.

Performing the posterior femoral cut parallel to the PCL (Kinematic Alignment) will internally rotate the trochlear groove of the femoral component more than three degrees in 47% of cases relative to the native rotation of the groove. Aligning the femoral component in an average position between the SL and PCL + 3° did not malrotate the alignment of the trochlear groove by more than three degrees from its native position in any cases (Table 3).

4. Discussion

The effect of the coronal alignment of the tibia in tipping the femur into internal or external rotation during flexion has not been widely considered. The main finding of this study is the strong correlation between the degree of tibial varus and increased FRA. The association was shown to be due to both increasing internal rotation of the posterior condyles and increasing external rotation of the trochlear groove as the tibial plateau becomes more varus (Figure 3). This suggests that there is a compensatory deformity in the femur to allow the trochlear groove to remain vertical during flexion in individuals with increasing tibial varus. Despite this correlation there is still a wide range of individual variation so each case should be individually assessed [16].

Luyckx et al. noted an association between rotational landmarks and overall coronal alignment by comparing tibiofemoral coronal alignment on preoperative CT scans [23]. They found a linear relationship between increasing tibiofemoral varus and internal rotation of the PCL. There was a significant but weaker association with the APA externally rotation with increasing tibiofemoral varus. These results are consistent with our findings, however we isolated the association to the proximal tibial varus not overall coronal alignment. Our study also found a stronger association between the trochlear rotational alignment and tibial coronal alignment by referencing the SL rather than the APA.

Luyckx et al. measured the tibiofemoral alignment on a long leg X-ray and predicted the angle between the posterior condyles and the SEA could be used to determine intraoperative rotation [23]. This approach does not account for the wide range of individual variation around the mean values. Their "Neutral group" had a mean difference between the PCL and SEA of −2.1° however the range was 11° from −5° to +6°. Setting rotation at 2.1° for each of these patients during surgery will produce a good average rotation but may malrotate many individual patients. Furthermore, the study ignores individual variations in rotational alignment of the trochlear groove.

There was no association in the current study between the coronal and rotational alignment of the distal femoral condyles. While there are likely to be a small number of individual cases in which valgus alignment of the distal femur is associated with a so-called hypoplastic lateral femoral condyle the relationship is inconsistent. The assumption should not be made that a valgus distal femur automatically has an internally rotated PCL.

The relationship between the PCL and the SEA has been well documented using many techniques including CT scans, MRI scans, computer navigation, cadaveric studies and intraoperative measurements. Griffin et al. measured a range of 0° to +10° (mean 3.7°) between the PCL and SEA intraoperatively [24]. Jones et al. used one hundred and eight 3D MRI scans and found a range from 0° to +6.9° between the PCL and SEA [25]. Twiggs et al. reviewed 726 arthritic knee CT scans finding range −4° to +8° (mean 1.9°) with 26% of patients still have a target for rotation greater than ±2° from the mean [12]. The results of the current study are similar with a range of −5.95° to +0.95° which is at the lower end of the variability seen in the other studies. The range of FRA in this study was 10.1°, which is less than in other reported series using the SL technique which used the intraoperative alignment guide [19]. Chao et al. showed a mean external rotation of the SL compared to the PCL of 1.4° and a range of 10.6° external to 6.3° internal rotation.

Restoring both tibiofemoral and patellofemoral rotational alignment utilizing symmetrical total knee arthroplasty components may be challenging [26]. Relying on one landmark to determine rotation may alter the rotation of the other landmark [12,19]. Table 3 shows how a technique only referencing the posterior condyles will frequently change the rotational alignment of the trochlear groove. The clinical relevance of this is difficult to predict however we know that when using mechanical alignment techniques internal rotation of the femoral component leads to poorer outcomes and increased patellofemoral symptoms [27–29]. In current practice components are positioned as close as possible to their native rotational alignment followed by appropriate ligament releases to maximize stability [30,31]. Custom implants may be able to recreate individual anatomy but this is technically challenging to perform accurately and still leaves a cruciate deficient knee [32]. Another option is to accept that it is impossible to recreate anatomy in many patients and therefore provide stability through more constrained prostheses such as medially stabilized components [33]. It is yet to be determined which of these philosophies is superior.

The concept that the trochlear groove becomes increasingly externally rotated as the proximal tibia becomes increasingly varus raises questions regarding the surgical technique known as Kinematic Alignment. Kinematic Alignment aims to reproduce the coronal alignment of the native tibial plateau and the rotational alignment of the posterior condyles [34,35]. It assumes that the trochlear groove is perpendicular to this rotational axis. By leaving the tibia in varus and inserting a symmetrical femoral component based solely on the PCL the situation depicted in Table 3 and Figure 2b occurs. This will lead to relative internal rotation of the trochlear groove relative to its native position by more than three degrees in 47% of individuals. A similar result was found by Park et al. using preoperative MRI scans and the APA rather than the more accurate SL technique [36]. They found that Kinematic Alignment would internally rotate the femoral component by on average 6.4° to a line perpendicular to the APA with a range from 1.5° externally rotated to 14.5° internally rotated.

Based on the concept of FRA it would seem prudent to measure the rotational alignment of both the trochlear groove and the posterior condyles in each case and determine a middle point between these in which to position the symmetrical prosthesis. Chao et al. incorporated this theory in a recent clinical trial using the Sulcus line of the Trochlear groove Alignment Guide

(STAG) device. It found that by accurately averaging the SL and PC + 3° it was possible to decrease the rate of femoral component rotation relative to the SEA down from 19% using the SL alone and 16% using the PC + 3° alone to two percent [19]. Paternostre et al. investigated the option of averaging the APA and PCL using preoperative MRIs [37]. They found much of variability in the combined landmark was due to the variability of the APA technique. Despite this they recommended combining landmarks to decrease variability and improve patellofemoral kinematics [19].

Limitations of this study include the use of arthritic knees. This makes it difficult to be certain how much of the variation is due to arthritis and how much is due to individual anatomical differences. It is also possible that arthritic knees may have a different rate or pattern of individual variation. There may also be increased measurement errors due to arthritic deformity. However, using arthritic knees can be seen to strengthen the study as it makes it more applicable to the clinical situation during knee arthroplasty.

Measurement errors occur in all studies of this type. We have attempted to decrease these errors by using the 3D CT scans, the more accurate SL technique and having each measurement performed by two blinded examiners. Furthermore, there was a wide range of individual variation between the rotational alignment of the distal femur and coronal alignment of the proximal tibia. A larger sample size could further strengthen our findings.

5. Conclusion

Native femora are frequently rotationally asymmetrical. Individuals with increasing proximal tibial varus are likely to have a more internally rotated PCL and an externally rotated trochlear groove. This asymmetry compensates for the effective internal rotation of the femur caused by tibial varus in a flexed knee by maintaining a more vertical trochlear groove.

Conflict of interest statement

One author (ST) receives royalties from Enztec for the STAG device mentioned in the study, however this study received no private or institutional funding.

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