Evolution of trochlear compartment geometry in total knee arthroplasty

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Background: The study aimed to compare trochlear profiles in recent total knee arthroplasty (TKA) models and to determine whether they feature improvements compared to their predecessors. The hypothesis was that recent TKA models have more anatomic trochlear compartments and would display no signs of trochlear dysplasia.

Methods: The authors analyzed the geometry of the 6 following TKA models using engineering software: PFC and Attune (DePuy), NexGen and Persona (Zimmer), Noetos and KneeTec (Tornier). The mediolateral trochlear profiles were plotted at various flexion angles (0°, 15°, 30° and 45°) to deduce the sulcus angle.

Results: Analysis of sulcus angles reveals general convergence of recent designs towards anatomic values. At 0° of flexion, sulcus angles of recent implant models were between 156.0–157.4°, while those of previous generation models between 154.5–165.5°. At 30° of flexion, sulcus angles of recent models also lie within 145.7–148.6°, but those of previous models are between 149.5–152.0°. All three manufacturers deepened their trochlear profile at 30° of flexion in recent models compared to earlier designs. Sulcus angles converge towards anatomic values but still exceed radiologic signs of dysplasia by 2–5°.

Conclusions: Recent TKA designs have more anatomic trochlear geometries than earlier TKA models by the same manufacturers, but trochlear compartments still exceed radiologic signs of trochlear dysplasia by 2° to 5°. The hypothesis that recent TKA models display no signs of trochlear dysplasia is therefore refuted. Surgeons should be aware of design limitations to optimize choice of implant and extensor mechanisms alignment. Level of evidence: IV geometric implant analysis.

Keywords: Total knee arthroplasty (TKA); component design; femoral trochlea; trochlear dysplasia

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Introduction

Total knee arthroplasty (TKA) is a successful procedure, with over 560,000 operations performed annually in Europe (1) and over 600,000 in the United States (2). Due to the ageing population, the number of TKA procedures is expected to rise almost four times by 2030 (3). Despite its success, a large proportion of patients experience pain and dissatisfaction after TKA, where patellofemoral pain and instability remain among the most common reasons for revision (4).

Anterior knee pain following TKA is observed equally in knees with resurfaced and non-resurfaced patellae (5-7), thus it is unlikely that pain is caused by arthritis of the patellar cartilage. Although the exact mechanism remains unclear, abnormal patellofemoral joint loads or kinematics caused by patellar malalignment, and over- and under-stuffing appear to play important roles in the development

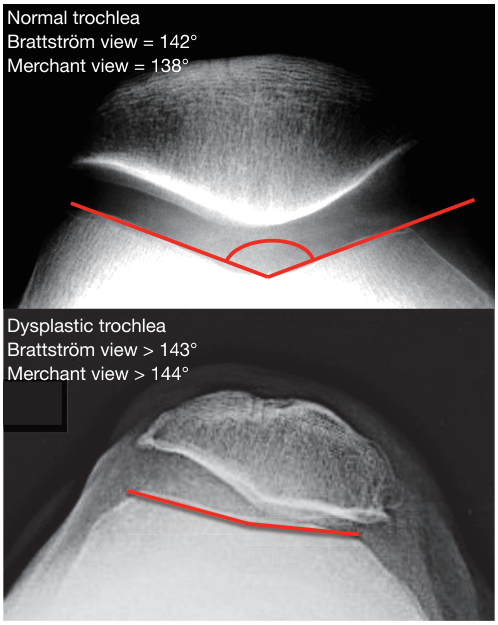

Figure 1 Illustration of trochlear sulcus angles measured on skyline radiographs in healthy and dysplastic knees.

of anterior knee pain (8-10). Patellar instability is a frequent complication after TKA that could lead to dislocation (5.8 per 100,000), which is of particular concern in young females (33 per 100,000) (11). It is caused by a variety of genetic, congenital, or sport-related factors (4,12): anatomic deformities, ligament malalignment, and neuromuscular activation.

Patellofemoral complications are usually caused by multiple factors related to surgical technique (e.g., implant positioning and sizing, soft-tissue balancing, patellar resurfacing, etc.) and implant design (e.g., trochlear depth, sagittal curvature, patellar component shape) (13-15). Numerous biomechanical studies suggest that even if the surgical technique is optimized, patellofemoral tracking is not always restored to physiological values, because the prosthetic trochlea may differ from the native trochlea, implying that complications may be due to implant design (14-17).

In 2010, the authors compared trochlear geometry in 14 TKA designs and found that most models exhibit characteristics of trochlear dysplasia (18). In a later study the authors found similar anomalies in patellofemoral arthroplasty (PFA) components (19). The principal parameter compared was the sulcus angle, a non-dimensional indicator often used to quantify the extent of trochlea dysplasia on skyline radiographs (*Figure 1*). The mean sulcus angle in normal knees is 138° in the 'Merchant view' at 45° of flexion (20,21), and 142° in the 'Brattström view' at 30° of flexion (22). The sulcus angle in knees with trochlear dysplasia is generally above 144° in the 'Merchant view' (23) or above 143° in the 'Brattström view' (24). In cases with severe patellofemoral disorders, such anatomic deformities can be addressed surgically by extensor mechanism realignment, trochleoplasty or tibial tuberosity osteotomy; and in the presence of arthritis, by partial or total arthroplasty (25-29).

The aim of the present study was to provide an updated analysis of trochlear geometry in more recent TKA models available globally, and to determine whether they feature improvements compared to their predecessors. The hypothesis was that recent TKA models have more anatomic trochlear compartments and would display no signs of trochlear dysplasia. Because patellofemoral complications are usually caused by multiple factors related to surgical technique and implant design, the authors did not attempt to correlate the findings with clinical results of the studied implants.

Material and methods

This is a descriptive study of the 6 following TKA femoral components: PFC and Attune (DePuy Orthopaedics Inc., Warsaw, IN, USA), NexGen and Persona (Zimmer Inc., Warsaw, IN, USA), HLS Noetos and KneeTec (Tornier SA, Montbonnot, France). Specimens were chosen from the middle of the available size range.

The specimens were each scanned using a three-dimensional (3D) optical scanning machine (ATOS II, GOM mbH, Braunschweig, Germany) and its photogrammetric analysis software (TRITOP, GOM mbH, Braunschweig, Germany). The system has measurement resolution of 0.05 mm and overall accuracy of ±0.01 mm. The coordinates of points scanned on each specimen were rendered into smooth surfaces using 3D model reconstruction software (Rapid Form, 3D Systems Corp., SC, USA), which enabled full manipulation and measurement using computer aided design software (Pro/Engineer, Parametric Technology Corporation, MA, USA).

The specimens were each oriented in a consistent coordinate system, with the origin defined as the intersection between the flexion-extension axis (centre of the cylinder that best fits the distal condyles) and the midpoint of the intercondylar notch. The authors plotted the trochlear profiles of the specimens at different flexion

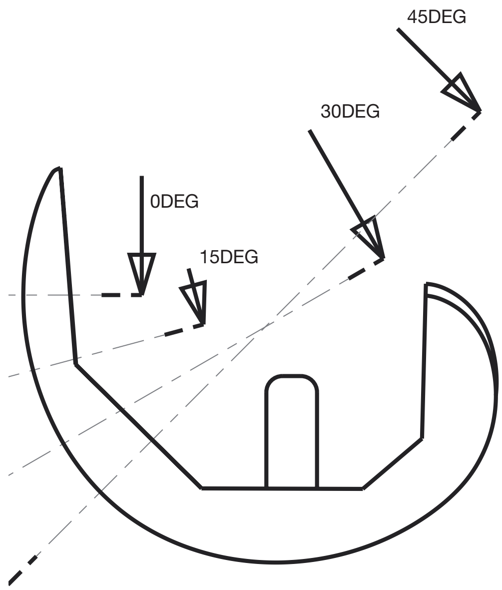

Figure 2 Illustration of trochlear profiles measured as viewed in the sagittal plane.

Table 1 Sulcus angles at various flexion angles

Variables	Degrees of flexion			
	0°	15°	30°	45°
Human knee				
Healthy trochlea			≈142°	≈138°
Dysplastic trochlea			>143°	>144°
DePuy				
PFC	154.5°	152.0°	149.7°	140.0°
Attune	157.4°	147.3°	146.7°	146.2°
Zimmer				
NexGen	160.8°	153.2°	149.5°	148.0°
Persona	156.1°	152.0°	148.6°	147.8°
Tornier				
Noetos	165.5°	156.0°	152.0°	135.7°
KneeTec	156.0°	155.0°	145.7°	153.0°

angles following a previously published protocol (18). Each specimen was virtually rotated about its flexion-extension axis using Pro/Engineer by the following angles: 0°, 15°, 30° and 45°. At each flexion angle, the most anterior point on the trochlea was marked and the mediolateral trochlear profile at that level was digitized (*Figure 2*).

All recorded coordinates were exported to spreadsheets using Microsoft® Excel (Microsoft Corp, Redmond, WA).

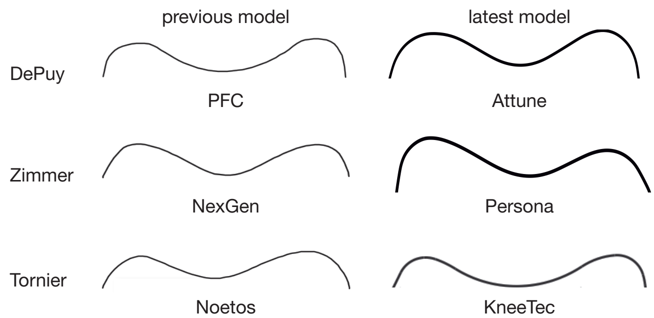

Figure 3 Trochlear profiles of all specimens at 30° of flexion.

To enable consistent geometric comparisons between all specimens, the coordinates of right-sided implants were mirrored to become super-imposable with those of left-sided implants. The two-dimensional ML profiles of each prosthetic trochlea could therefore be superposed and compared with its origin at the intersection of (I) the midpoint between the medial and lateral margin of each specimen and (II) the trochlear groove, or deepest point on the sulcus, of each profile. The 'sulcus angle' of each profile was calculated from the coordinates of the trochlear groove and those of the highest points of the medial and lateral facets.

As this study did not involve human nor animal data, institutional review board (IRB) was not required, and statistical analysis was not performed.

Results

The sulcus angles of all implants were compared (*Table 1*) and the trochlear profiles at 30° of flexion were presented visually in a non-dimensional coordinate system (*Figure 3*). Analysis of sulcus angles reveals general convergence of designs to anatomic values.

At 0° of flexion, sulcus angles of recent implant models lie within the narrow range of 156.0° to 157.4°, while those of previous generation models are spread across a wide range of 154.5° to 165.5°. Comparison of DePuy implants revealed that the more recent Attune model has a trochlea 3° shallower than that of the earlier PFC model. By contrast, the Zimmer and Tornier implants revealed that the more recent Persona and KneeTec respectively have trochlea 4.7° and 9.5° deeper than those of the earlier NexGen and Noetos models.

At 30° of flexion, sulcus angles of recent implant models also lie within a limited range of 145.7° to 148.6°, but those of previous generation models are within a similar range of 149.5° to 152.0°. All three manufacturers have deepened their trochlea at 30° of flexion in the more recent models compared to earlier designs. While the sulcus angles converge towards anatomic values, they remain 3° to 6° shallower than average values reported for healthy knees.

At 45° of flexion, the sulcus angles of recent models vary within the range of 146.2° to 153.0°, and those of previous generation models are equally spread from 135.7° to 148.0°. Both DePuy and Tornier have reduced the depth of the trochlea in their recent models compared to previous models, whereas the trochlea of Zimmer implants remained unchanged at that level. It is worth noting that sulcus angle measurements at 45° of flexion in TKA models are inconsistent due to the presence of an intercondylar notch or a post-cam mechanism.

Discussion

The principal finding of this study was that recent TKA designs have more anatomic trochlear geometries than earlier TKA models by the same manufacturers. The sulcus angles remain 3° to 6° greater (shallower) in prosthetic trochlear compartments than in healthy knees, and they exceed radiologic signs of trochlear dysplasia by 2° to 5°. The hypothesis that recent TKA models display no signs of trochlear dysplasia is therefore refuted.

In a previous study of 14 TKA designs, the authors reported that 11 models had sulcus angles that exceeded radiographic indicators of trochlear dysplasia, and that in most models the discrepancy was over 10°. The sulcus angle is inversely proportional to the depth of the trochlear groove, which is important to engage the patella in the trochlea, especially in early flexion (0° to 30°) (29-31). The average sulcus angle for healthy knees is 138° in the 'Merchant view' (20,21,32), and 142° in the 'Brattström view' (22). A high sulcus angle indicates a shallow or dysplastic trochleae, observed in the majority of patients suffering from patellofemoral disorders (33). On the other hand, a normal sulcus angle does not exclude the presence of trochlear dysplasia, since sulcus angle may be high proximally and decrease distally to normal values (34-36).

The design of the femoral component is of great importance to grant normal kinematics and inappropriate trochlear groove geometry could induce patellofemoral complications following TKA (37). In the past, the inability of implant manufacturers to replicate normal trochlear anatomy was attributed to lack of anatomic data from healthy trochlear grooves (15,30,31), but numerous morphometric studies were published in recent years to help prevent such discrepancies between normal and prosthetic anatomy (16,18,19,31,38-48).

Trochlear components with high sulcus angles require a specific and adapted surgical technique including ligament balancing and extensor mechanism realignment according to the TT-TG value to prevent any further patellar maltracking in early flexion. If the patella is resurfaced, the shape of the patellar button could influence patellofemoral tracking and stability, but this aspect was not considered in the present analysis as all models included can be implanted without patellar resurfacing.

The authors recently studied how the *in-vivo* position of the patella in mid-flexion can be influenced by design enhancements to the trochlear compartment and patellar button in the HLS KneeTec compared to its predecessor the HLS Noetos (38). While the tibiofemoral kinematics were nearly identical for both implant studied, the patellar flexion angle was significantly using the KneeTec component (23.5°±8.7°) than using the Noetos component (6.3°±7.3°). Since the same surgical technique and implant alignment were used for both implant models, it is likely that the differences in post-operative patellar position are related to the differences in trochlear geometry and patellar design between the two implant models. The authors noted that the 'cone-shaped' button of the Noetos tilts until equilibrium is reached, whereas the 'dome-shaped' button of the KneeTec resists tilt by virtue of its large-radius spherical surface (49).

The strengths of this study were the ability to directly compare current and preceding TKA models by the same manufacturers to assess the evolution of trochlear geometry in the light of published morphometric studies and kinematic investigations on the patellofemoral joint. The measurement techniques were consistent and reproducible. In addition, the 'scale factor' was minimized by studying specimens from the middle of the size range and by referring to a non-dimensional variable of sulcus angle. The main weaknesses of the study were the consideration of the trochlear component and not the patellar component, and the focus on static design features rather than dynamic implant performance.

Conclusions

The present study reveals that recent TKA designs have more anatomic trochlear geometries than earlier TKA models by the same manufacturers, but the trochlear compartments still exceed radiologic signs of trochlear dysplasia by 2° to 5°. The clinical relevance of this descriptive study is that surgeons should be aware of such design limitations in order to improve their choice of implants for specific patients, and to improve diagnosis and treatment of post-operative patellofemoral complications. The authors stress the importance of assessing patellar tracking intra-operatively to ensure that the extensor mechanisms is optimally adjusted and that the implant configuration grants adequate patellar stability particularly in early flexion.

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Footnote

Conflicts of Interest: The authors have no conflicts of interest to declare.

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