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CLINICAL RESEARCH

The Geometry of the Trochlear Groove

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Abstract
Background In the natural and prosthetic knees the position, shape, and orientation of the trochlea groove are three of the key determinants of function and dysfunction, yet the rules governing these three features remain elusive.
Questions/Purpose The aim was to define the three-dimensional geometry of the femoral trochlea and its relation to the tibiofemoral joint in terms of angles and distances.
Methods Forty CT scans of femurs of healthy patients were analyzed using custom-designed imaging software. After aligning the femur using various axes, the locations and orientations of the groove and the trochlear axis were examined in relation to the conventional axes of the femur.
Results The trochlear groove was circular and positioned laterally in relation to the mechanical, anatomic, and transcondylar axes of the femur; it was not aligned with any of these axes. We have defined the trochlear axis as a line joining the centers of two spheres fitted to the trochlear surfaces lateral and medial to the trochlear groove. When viewed after aligning the femur to this new axis, the trochlear groove appeared more linear than when other methods of orientation were used.
Conclusions Our study shows the importance of reliable femoral orientation when reporting the shape of the trochlear groove.

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Each author certifies that his or her institution has approved the human protocol for this investigation, that all investigations were conducted in conformity with ethical principles of research, and that informed consent for participation in the study was obtained.
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Introduction

Despite the current success of TKA, patellofemoral complications are a common postoperative problem and also one of the causes for revision surgery [1, 6–8, 16, 19]. The design of the prosthetic groove is one of the determinants of patellofemoral outcome after TKA [17]. This element of total knee prostheses has evolved substantially, with different design strategies used to relate the trochlea component to the tibiofemoral articulation reflecting the understanding of their relationship and the technologies involved in design and manufacture. Most recent designs have evolved to become more anthropomorphic in the way in which the trochlea part of a total knee prosthesis is related to the tibiofemoral part, but without an explicitly stated rationale for the size, shape, and position of the trochlea in relation to the rest of the joint. With the advent of novel patellofemoral and unicompartmental arthroplasties

[18, 20], these relationships may have even more importance.

Although the geometry of the trochlear groove has been investigated, its alignment and relation to the tibiofemoral joint remain unclear. Previous studies used various methods such as photography, plain radiographs, unreconstructed CT scans, and direct measurement tools like probes and micrometers to define the morphologic features of the trochlear groove with differing results [3, 9, 11, 22]. The variation can in some part be attributed to the lack of reliable orientation of the femur. An accurate description of the three-dimensional (3-D) geometry and alignment of the natural femoral trochlea would provide a basis for evaluation of the designs of prostheses.

We sought to define the 3-D geometry of the femoral trochlear groove and examine its relationship with the other axes of the distal femur. This may allow better understanding of the variation in the relationship between the components of the normal knee in contrast to the fixed relationships and shapes of differing designs of knee prostheses. It was anticipated that the use of novel software to examine the 3-D image reconstructions would lead to a more accurate description of the relationships between the different compartments of the normal knee.

The two primary aims of this study therefore were to define the geometry of the trochlea and to study how its relationship with the tibiofemoral joint could be described. It was hypothesized that the 3-D analysis would allow identification of geometric relationships between the trochlea and the rest of the femur and its axes in terms of angular orientation and distances in all three planes: coronal, sagittal, and transverse. We suggest that a novel trochlear axis can be found, and that the size, position, and orientation of the trochlea can be described using this axis in relation to other axes in the femur. The trochlear axis also may be of use during arthroplasty in cases with severe bone loss from the condyles and even epicondyles. A secondary aim was to determine the effect of changing the orientation of the view of the femur on describing the shape of the trochlear groove.

Patients and Methods

Forty CT scans of the normal knees of patients older than 55 years were performed in extension. These patients were scanned as part of another study that examined hip disease. In case of hip abnormality, the contralateral knee was selected for this study. Patients with a history of knee instability or pain and patients with radiographic changes were excluded. We obtained the scans using an established protocol that reduced the total radiation exposure to 0.7 mSev, the same radiation dose as that from a long-leg standing film [15]. Three-dimensional images were reconstructed using computer software that enabled manipulation of these images and for measurements to be taken. The accuracy of the method used was comparable to that obtained with the Faro digitizing arm and digital caliper with the differences between the measurements within 0.5 mm and 1°. Two spheres could be fitted to femoral condyles (radius of 20 ± 2 mm for the medial and 19 ± 2 mm for the lateral condyle), and the transcondylar axis was defined as a line connecting the centers of these spheres. The frame of reference of the femur was established as a plane fitted to the center of the femoral head and the centers of two spheres fitted to the posterior parts of the femoral condyles (Fig. 1A–B). The epicondylar axis was a line that passed through the medial epicondylar sulcus and the most prominent point of the lateral epicondyle (Fig. 1C).

We derived the interobserver variability for finding the centers of the condyles using two observers (FI, WD) by comparing the coordinates of these centers with a fixed reference point and the maximum angle of the transcondylar axis relative to a fixed reference line on every scan. The average difference between the coordinates for the centers of the spheres as determined by two observers was less than 1 mm. The average root mean square difference of the angle between the transcondylar axes defined by two observers was 1°. There was strong agreement between the readings of the two observers; the intraclass correlation coefficient for orientation of the trochlear axis was 0.97.

The path of the trochlear groove was defined by identifying 12 points in the deepest part of the trochlear groove using all three planes on the CT images (Fig. 2A). A circle could be fitted to these points with low error (average root mean square error of 0.3 mm). The best-fit circle was found using a software routine that minimized the root mean square error in relation to the 12 points. We measured the angles between the trochlear groove circle and the transcondylar and epicondylar axes in the transverse and coronal planes (Fig. 2B–C). The position of the center of the trochlea groove circle in relation to the transcondylar axis in the sagittal plane was determined as proximodistal and anteroposterior offsets and the angle in the sagittal plane between the line connecting the center of the groove to the transcondylar axis and the femoral frame of reference (Fig. 2D).

To investigate the effect of orientation of the femur on the description of shape and orientation of the trochlear groove, we measured the mediolateral position of the trochlear groove points in relation to the center of the knee (the midpoint [D] between the centers of the spheres fitted to the posterior parts of the femoral condyles) after aligning the femur in the sagittal plane using different axes (anatomic, transcondylar, mechanical, trochlear axes) (Fig. 3).

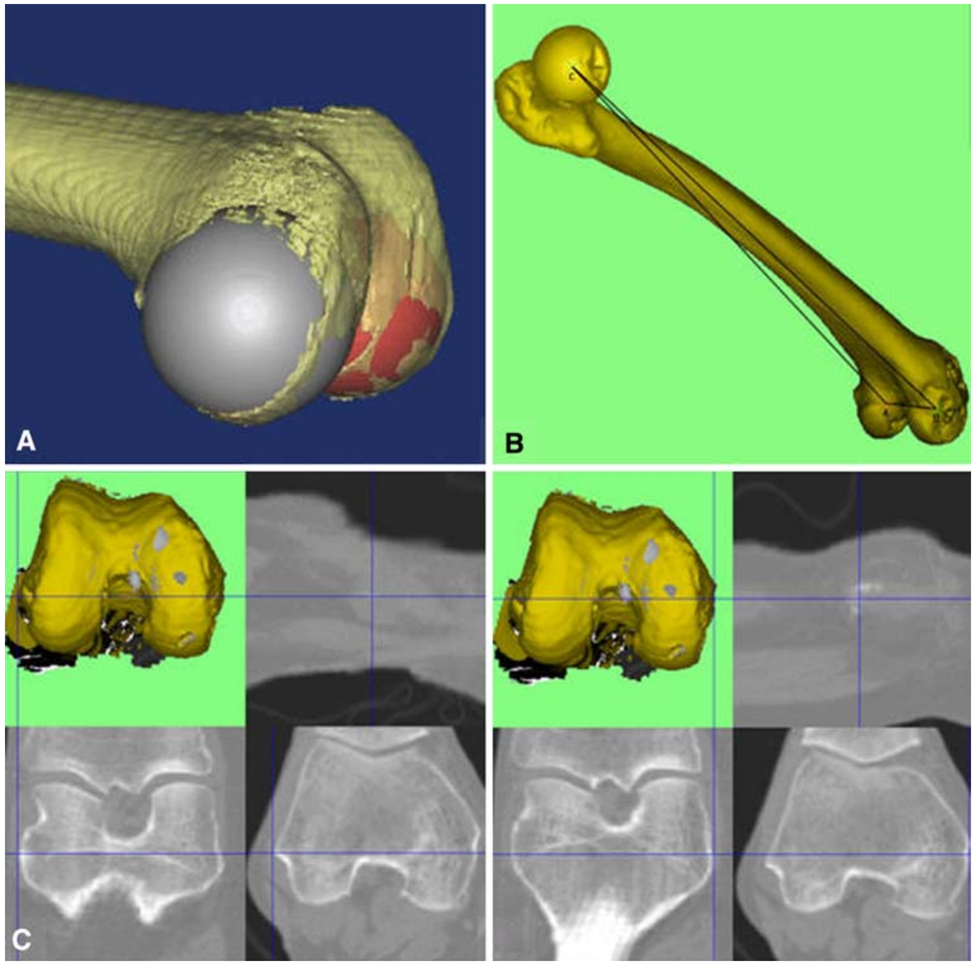

Fig. 1A–C (**A**) Two spheres could be fitted to the femoral condyles and the transcondylar axis was defined as a line connecting the centers of these spheres. (**B**) The frame of reference of the femur was defined as the plane joining the center of the femoral head and the centers of the spheres fitted to the femoral condyles. (**C**) The surgical epicondylar axis was established as the line connecting the tip of the lateral epicondyle (shown in the two left images) and the deepest point on the medial epicondyle sulcus (from another CT slice, shown in the two right images).

Results

We found that the geometry of the trochlear groove could be characterized in simple terms, because the points lying along the deepest points on the trochlear groove could be fitted accurately to a circle. This circle had an average radius of 23 ± 4 mm (16–34 mm; mean ± standard deviation; minimum-maximum) and the data points had an average root mean square error of 0.3 mm from the circle in each knee. The surface of the trochlea on either side of the groove was part spherical with radii of 30 ± 4 mm (24–41 mm) and 27 ± 4 mm (20–37 mm) for the lateral and medial trochlear surfaces, respectively. We named the transverse line joining the centers of these spheres 'the trochlear axis'.

We found orientation of this trochlear axis and its relationship with the other anatomic and mechanical axes of the femur could be defined consistently with reference to the major anatomic planes. In the transverse plane, which shows internal-external rotation, the transcondylar and trochlear axes were close to being parallel with an average angle between them of 0° ± 3°. The epicondylar axis was externally rotated by 2.5° ± 2.5° in relation to the transcondylar axis. The line of the trochlear groove (defined from the deepest points, which were fitted to the circle) was close to being in the sagittal plane, being only an average of 1° ± 5° (−11°–10°) externally rotated relative to the transcondylar axis in the transverse plane.

In the coronal plane, which shows varus-valgus rotation, the transcondylar and trochlear axes were close to being parallel with the trochlear axis in relative varus rotation of 2° ± 3°. The line along the deepest points of the trochlear groove was aligned 1° ± 5° (−10°–11°) in valgus relative to perpendicular to the transcondylar axis. The epicondylar axis was in varus by 1° ± 2.1° in relation to the transcondylar axis. In the sagittal plane, the point at the center of the trochlear groove circle can be found 9 ± 2.5 mm (3–16 mm) proximal, and 18 ± 2.3 mm (14–23 mm) anterior to the transcondylar axis. Alternatively, the point can be found 20 mm in a direction of 66° ± 7.5° (47°–83°) anteroproximal from the transcondylar axis (Fig. 2D).

Changing orientation of the view of the femur did change the described shape of the trochlear groove. The transepicondylar width of the distal femur was 79.5 ± 6.5

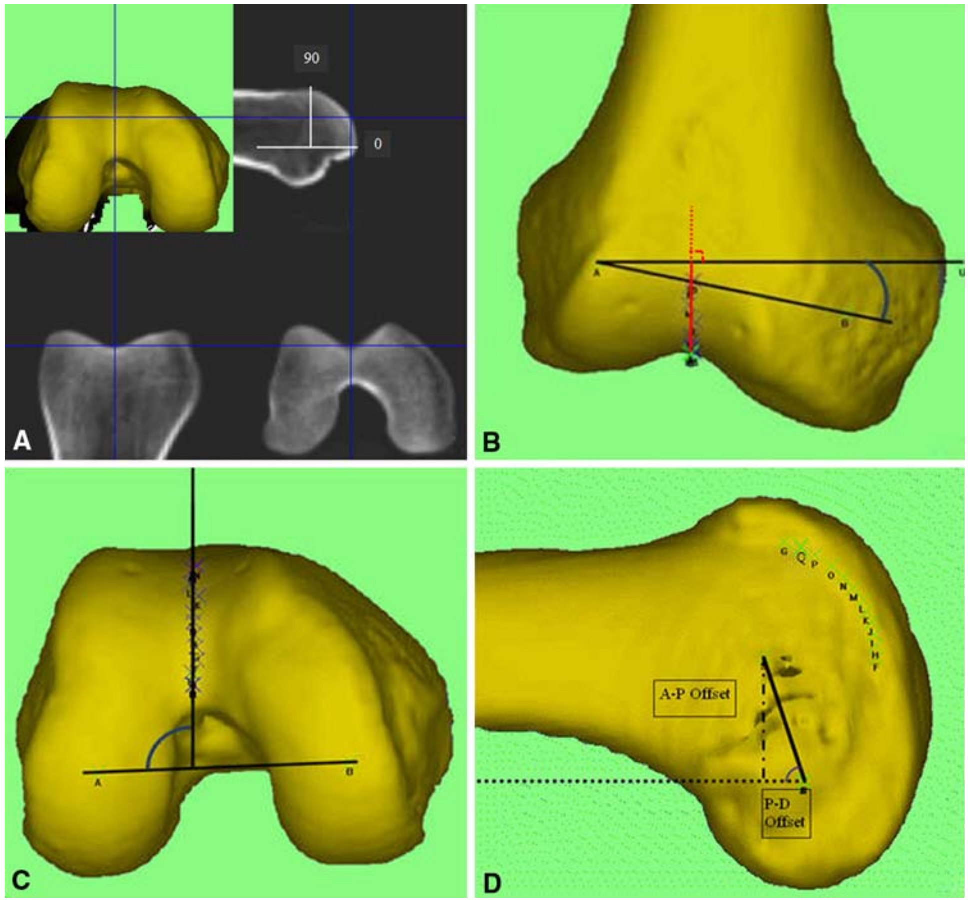

Fig. 2A–D (**A**) The geometry of the trochlear groove was established by finding the deepest points of the trochlea using the quad image option of the software, which enabled us to pick our points considering all three planes (sagittal, coronal, and transverse). The most posterior point was set as 0 and most proximal as 90. Ten more points were selected in the trochlear groove between these two points. Then the best fit circle was established and the center and the radius of it were found. The angle measured between the plane fitted to the deepest points on the trochlea and the transcondylar axis in the (**B**) coronal and (**C**) transverse planes. Line AU is perpendicular to the plane of the circle fitted into the groove. (**D**) In the sagittal plane, the angle between the center of the circle fitted to the trochlear groove and the reference plane (∼), the anteroposterior and proximodistal distances between this center, and the center of the medial condyle were measured.

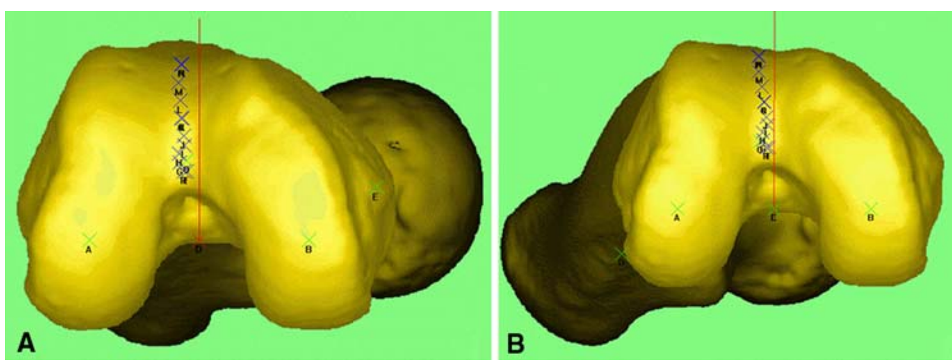

Fig. 3A–B The mediolateral position of the trochlear groove in relation to the center of the knee after aligning the femur in the sagittal plane using (**A**) anatomic and (**B**) mechanical axes is illustrated.

(standard deviation) mm. The starting point in the groove posteriorly was 4.2 ± 1.3 mm (1.6–7.4 mm) lateral to the anatomic axis. To eliminate the effect of the variable distance between the trochlear groove points and the midpoint between the condyles, the starting point in the groove posteriorly (in the notch) was set as zero. The average ranges of mediolateral deviation of the trochlear groove points from the center were measured as 1.5 ± 1.4 mm, 1.4 ± 1.6 mm, 1 ± 1.6 mm, and 0.9 ± 1.2 mm after aligning the femur to transcondylar, mechanical, anatomic, and trochlear axes, respectively (Fig. 4). Thus, if the measurements are not aligned accurately with the groove, perpendicular to the trochlear axis, it will appear to have larger mediolateral deviations.

The average difference between the mediolateral positions of the trochlear groove points measured by two observers for measuring 12 points in 10 knees was less than 1 mm.

Discussion

This study of the 3-D geometry of the normal distal femur showed that the trochlea can be described accurately by a

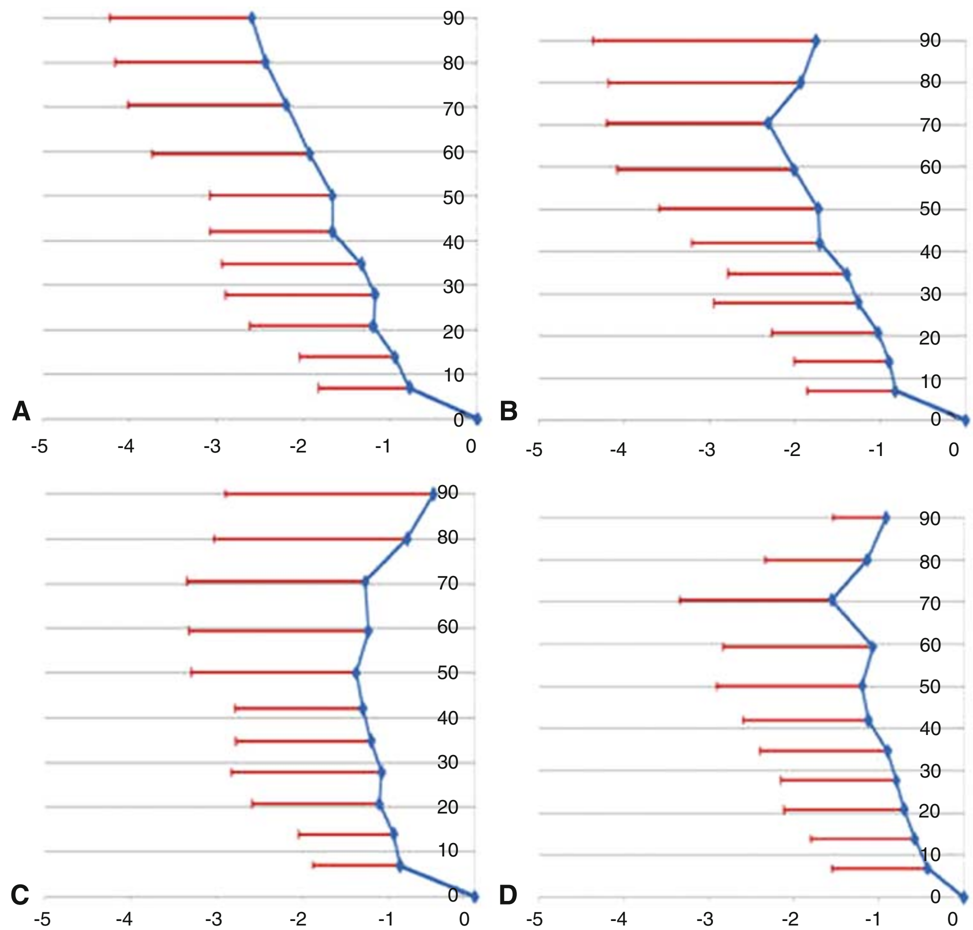

Fig. 4A–D The effect of orientation on the apparent mediolateral translation of the trochlear groove is shown. The groove started at the (0,0) origin of each graph when the knee was in extension. As the knee flexed toward 90° (along the vertical axis of each graph), the groove appeared to deviate laterally in relation to the starting point, shown along the X axis in millimeters after the femur was aligned to (**A**) mechanical, (**B**) anatomic, (**C**) transcondylar, and (**D**) trochlear axes.

circle fitted to the bottom of the trochlear groove, with part-spherical articular surfaces medial and lateral to it. We also introduced a novel trochlear axis, which is the line that joins the centers of these two spheres. We observed consistent relationships of the alignment and position of the trochlear axis to the epicondylar and condylar axes of the tibiofemoral joint. Thus, results of our study provide a basis for designing the correct relationship between the two sets of articular surfaces in the femoral component of a total knee prosthesis, correct placement of the femoral component of a patellofemoral joint prosthesis in relation to the femoral condyles, and the means to identify abnormalities such as dysplasia or arthritic erosions of the natural trochlea.

The trochlear groove plays a major role in the mechanics and pathomechanics of the patellofemoral joint [13, 14, 21]. After knee arthroplasty, one of the determinants in the patellofemoral mechanism is the design of the prosthetic trochlear groove [17]. Modern knee arthroplasty implants have more anatomic patellofemoral designs, but still a clear and accurate description of the size, shape, and position of the trochlea in relation to the medial and lateral compartments is lacking in the literature. The primary aim of this study was to describe the 3-D geometry of the femoral trochlear groove and its relationships in the knee. It was anticipated that manipulation of the full 3-D data set would allow insights that would allow the trochlear geometry to be defined in simple terms such as angular orientation or position, similar to the study by Eckhoff et al. [9]. The secondary aim was to determine the effect of orientation of the femur on describing the morphologic features of the trochlear groove, which may be the cause of variable results from previous published studies.

A shortcoming of our study was the use of CT scans, which do not show the cartilaginous surfaces of the distal femur. Although two studies have shown the geometry of the cartilage surface differed from that of the bone in the trochlea, the difference was small [22, 23]. CT has a higher resolution and linearity than MRI; thus, it has the advantage that it will produce better 3-D images and allow more accurate measurements in multiple planes.

The primary aim, to establish a reliable and simple description of the 3-D geometry of the femoral trochlear groove, has been achieved. The trochlear groove can be described simply as part of a circle. This circle was positioned lateral to the anatomic and mechanical axes. This position did not match the data of Shih et al. [22]. This may be a result of our different definitions of the center of the knee. On average, the plane fitted to the trochlear groove was within 1° of being in the sagittal plane, perpendicular to the transcondylar axis. Thus, in a distoproximal view, the plane of the groove approximated Whiteside's line, as described by Arima et al. [2]. In the sagittal view, the center of this circle was offset 21 ± 3 mm from the transcondylar axis, or 20 mm from the transcondylar axis at an angle of 66° ± 8° anteroproximal from the frame of reference of the femur (Fig. 2D).

The method of measurements we used, based on reliably orientating the femur in three dimensions, and deriving the centers of spherical surfaces from many surface points is likely to be as accurate as any other method. The measurements we obtained, based on 3-D images and the use of Hounsfield units to correctly identify bony limits, further improve the repeatability of this observation.

The secondary aim also was achieved by showing the effect of orientation of the femur on reporting the geometry of the trochlear groove. Previous investigators have described the trochlear groove as linear or bilinear [3, 10]. A bilinear description is obtained by fitting two lines to the points that describe the groove, one for each of the proximal and distal areas. Our results simply show the circular path of the trochlear groove can be described as linear or bilinear depending on orientation of the femur. Therefore any description of the anatomic design, whether linear or bilinear, also needs to have a precise definition of the frame of reference used to describe it. This also affects the description of patellar kinematics in relation to the distal femur in the same way [5]. In our study, the trochlear groove had the least mediolateral deviation when it was aligned to the trochlear axis, so it is most linear in this orientation. When surgery to the patellofemoral joint alone is envisaged, this may be of value, whereas the compromises needed in TKA also will be more easily appreciated.

We also introduced the trochlear axis as a new axis in the distal femur. The relation between this axis and the trochlear groove and the transcondylar axis is reported. This axis has numerous potential uses in preoperative planning of cases with severe tibiofemoral disease in which the posterior condyles are damaged and even the surgical epicondylar axis could not be reliably defined [24].

Patellofemoral symptoms can be the result of abnormal patellofemoral forces, which are caused mostly by changes in the tracking pattern. However, although the design of the components is a crucial factor affecting the postoperative patellar tracking pattern after knee arthroplasty, it also is determined by alignment, soft tissue releases, scar tissue, and the surgery in general. The question regarding whether an asymmetric or laterally positioned trochlear groove would result in more physiologic patellofemoral biomechanics remains unresolved [4, 12]. The knowledge of the shapes of the surfaces of this joint and their relations to the alignment of the femur may help to identify and quantify trochlea dysplasia and other disorders relating to patellar maltracking. It also may be of use in planning and performing joint reconstruction. Finally, documentation of these relationships in the normal knee may have implications for the design of patellofemoral and variations of partial and total knee prostheses and the rules governing their relative positions and sizes. When these methods are applied to abnormal trochleas, it may be possible to establish which departures from the normal relationship are most prone to result in development of symptomatic disease.

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References

1. Aglietti P, Buzzi R, Gaudenzi A. Patellofemoral functional results and complications with the posterior stabilized total condylar knee prosthesis. *J Arthroplasty*. 1988;3:17–25.
2. Arima J, Whiteside LA, McCarthy DS, White SE. Femoral rotational alignment, based on the anteroposterior axis, in total knee arthroplasty in a valgus knee: a technical note. *J Bone Joint Surg Am.* 1995;77:1331–1334.
3. Barink M, van de Groes S, Verdonschot N, de Waal Malefijt M. The trochlea is bilinear and oriented medially. *Clin Orthop Relat Res.* 2003;411:288–295.
4. Barink M, Meijerink H, Verdonschot N, van Kampen A, de Waal Malefijt M. Asymmetrical total knee arthroplasty does not improve patella tracking: a study without patella resurfacing. *Knee Surg Sports Traumatol Arthrosc*. 2007;15:184–191.
5. Bull AM, Katchburian MV, Shih YF, Amis AA. Standardisation of the description of patellofemoral motion and comparison between different techniques. *Knee Surg Sports Traumatol Arthrosc*. 2002;10:184–193.
6. Callahan CM, Drake BG, Heck DA, Dittus RS. Patient outcomes following tricompartmental total knee replacement: a meta-analysis. *JAMA.* 1994;271:1349–1357.
7. Clayton ML, Thirupathi R. Patellar complications after total condylar arthroplasty. *Clin Orthop Relat Res.* 1982;170:152–155.
8. Dennis DA. Patellofemoral complications in TKA: a literature review. *Am J Knee Surg.* 1992;5:156–161.
9. Eckhoff DG, Bach JM, Spitzer VM, Reinig KD, Bagur MM, Baldini TH, Rubinstein D, Humphries S. Three-dimensional morphology and kinematics of the dorsal part of the femur viewed in virtual reality: Part II. *J Bone Joint Surg Am*. 2003; 85(suppl 4):97–104.
10. Eckhoff DG, Burke BJ, Dwyer TF, Pring ME, Spitzer VM, VanGerwen DP. The Ranawat Award. Sulcus morphology of the distal femur. *Clin Orthop Relat Res.* 1996;331:23–28.
11. Feinstein WK, Noble PC, Kamaric E, Tullos HS. Anatomic alignment of the patellar groove. *Clin Orthop Relat Res.* 1996;331:64–73.
12. Freeman MA, Samuelson KM, Elias SG, Mariorenzi LJ, Gokcay EI, Tuke M. The patellofemoral joint in total knee prostheses: design considerations. *J Arthroplasty.* 1989;4(suppl):S69–S74.

13. Fulkerson JP, Hungerford DS. Normal anatomy. In: Fulkerson JP, Hungerford DS, eds. *Disorders of the Patellofemoral Joint.* Baltimore, MD: Williams & Wilkins; 1990:1–24.
14. Fulkerson JP, Hungerford DS. Biomechanics of the patellofemoral joint. In: Fulkerson JP, Hungerford DS, eds. *Disorders of the Patellofemoral Joint*. Baltimore, MD: Williams & Wilkins; 2004: 25–41
15. Henckel J, Richards R, Lozhkin K, Harris S, Baena FM, Barrett AR, Cobb JP. Very low-dose computed tomography for planning and outcome measurement in knee replacement: the Imperial knee protocol. *J Bone Joint Surg Br.* 2006;88:1513–1518.
16. Huo MH, Sculco TP. Complications in primary total knee arthroplasty. *Orthop Rev.* 1990;19:781–788.
17. Kulkarni SK, Freeman MA, Poal-Manresa JC, Asencio JI, Rodriguez JJ. The patellofemoral joint in total knee arthroplasty: is the design of the trochlea the critical factor? *J Arthroplasty.* 2000;15:424–429.
18. Lonner JH. Modular bicompartmental knee arthroplasty with robotic arm assistance. *Am J Orthop*. 2009;38(2 suppl):28–31.
19. Noble PC, Conditt MA, Cook KF, Mathis KB. The John Insall Award. Patient expectations affect satisfaction with total knee arthroplasty. *Clin Orthop Relat Res.* 2006;452:35–43.
20. Rolston L, Siewert K. Assessment of knee alignment after bicompartmental knee arthroplasty. *J Arthroplasty*. 2009;24: 1111–1114.
21. Senavongse W, Amis AA. The effects of articular, retinacular, or muscular deficiencies on patellofemoral joint stability. *J Bone Joint Surg Br*. 2005;87:577–582.
22. Shih YF, Bull AM, Amis AA. The cartilaginous and osseous geometry of the femoral trochlear groove. *Knee Surg Sports Traumatol Arthrosc*. 2004;12:300–306.
23. Stäubli HU, Dürrenmatt U, Porcellini B, Rauschning W. Anatomy and surface geometry of the patellofemoral joint in the axial plane. *J Bone Joint Surg Br.* 1999;81:452–458.
24. Yoshino N, Takai S, Ohtsuki Y, Hirasawa Y. Computed tomography measurement of the surgical and clinical transepicondylar axis of the distal femur in osteoarthritic knees. *J Arthroplasty.* 2001;16:493–497.