Assessment of the Radii of the Medial and Lateral Femoral Condyles in Varus and Valgus Knees with Osteoarthritis

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Background: Understanding the relationship between the radii of the medial and lateral femoral condyles in varus and valgus knees is important for aligning the femoral component and for restoring kinematics in total knee arthroplasty. The purpose of this study was to test the hypothesis that the asymmetry between the radii of the medial and lateral femoral condyles in varus and valgus knees with osteoarthritis is small enough to be clinically unimportant.

Methods: A magnetic resonance imaging scan was obtained with use of a biplanar, rotational alignment protocol in a consecutive series of subjects with end-stage osteoarthritis prior to total knee arthroplasty. The alignment protocol oriented the scanning plane so that both condyles were imaged in a plane perpendicular to the primary femoral axis of the knee about which the tibia flexes and extends. The study included 155 varus knees and forty-four valgus knees. Radii were calculated from the area of the best-fit circle overlaid from 10° to 160° on the subchondral corticocancellous bone interface of the medial and lateral femoral condyles. The radius of a condyle was the average of the radii on four adjacent images that showed the femoral condyle with the largest curvature.

Results: In the 155 varus knees, the radius of the lateral condyle was an average of 0.1 mm larger than that of the medial condyle ($p = 0.003$). In the forty-four valgus knees, the radius of the lateral condyle was an average of 0.2 mm larger than that of the medial condyle ($p < 0.006$). There was a strong association between the radii of the medial and lateral femoral condyles in both the varus ($r^2 = 0.9210$) and the valgus ($r^2 = 0.9129$) knees.

Conclusions: As determined by imaging of the femoral condyles perpendicular to the primary femoral axis of the knee, the asymmetry between the radii of the medial and lateral femoral condyles in varus and valgus knees with end-stage osteoarthritis was ≤0.2 mm, which is small enough to be considered clinically unimportant when aligning a total knee prosthesis.

Knowing whether there is a difference between the radii of the medial and lateral femoral condyles in both varus and valgus knees with osteoarthritis is important for understanding the kinematics of the knee and for the three-dimensional alignment of the femoral component of a total knee prosthesis[1,2]. A comprehensive description of the kinematics of the normal knee requires knowledge of the three-dimensional orientation and interrelationship of the three axes of the knee about which motion occurs (Fig. 1)[3]. In terms of aligning the femoral component, the most important kinematic axis of the knee passes through the center point of the best-fit circles of the medial and lateral femoral condyles and is termed the *primary femoral axis about which the tibia flexes and extends*[3-7]. A second axis, also in the femur, is oriented parallel, proximal, and anterior to the primary femoral axis and is termed the *secondary femoral axis about which the patella flexes and extends*[3]. A third axis, in the tibia, is oriented perpendicular to both the primary and the secondary femoral axis and is termed the *longitudinal tibial axis about which the tibia internally and externally rotates on the femur*[3,7]. The foundation for restoring normal kinematics in total knee arthroplasty is alignment of the axis of the femoral component coincident with the primary femoral axis of the knee[3,6,7]. If there is a clinically relevant asymmetry between the radii of the best-fit circles of the medial and lateral femoral condyles in varus and valgus osteoarthritic knees, then accounting for this

Disclosure: The authors did not receive any outside funding or grants in support of their research for or preparation of this work. One or more of the authors, or a member of his or her immediate family, received, in any one year, payments or other benefits in excess of $10,000 or a commitment or agreement to provide such benefits from commercial entities (Biomet Sports Medicine and OtisMed, Inc.).

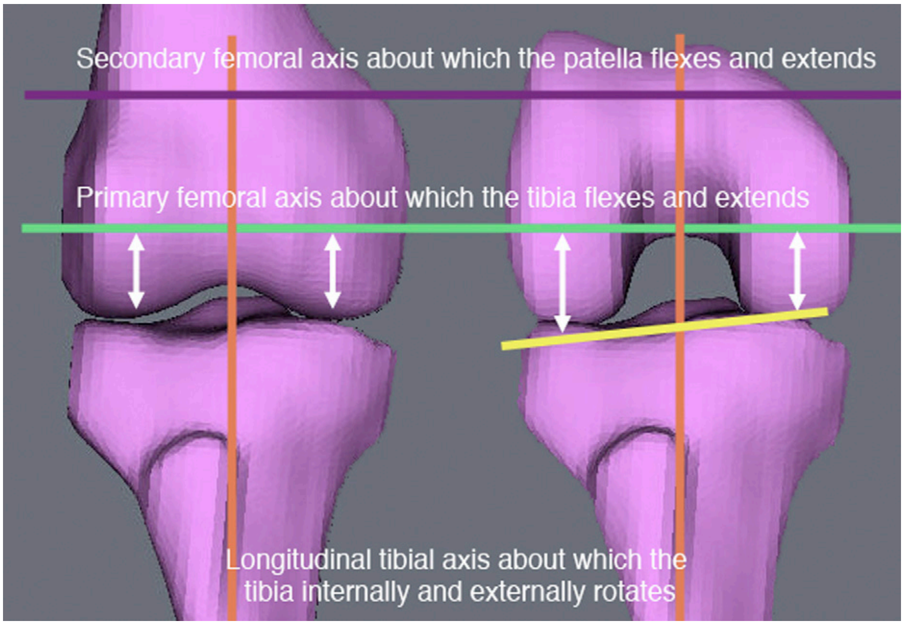

Fig. 1

A schematic diagram of a right knee with the interrelationship of the three kinematic axes. On the left is the coronal projection with the knee in extension. On the right is the axial projection with the knee in 90° of flexion. The most important kinematic axis of the knee passes through the center point of the best-fit circles of the medial and lateral femoral condyles and is termed the *primary femoral axis about which the tibia flexes and extends* (transverse green line); the axis is equidistant from the distal and posterior articular surfaces of the condyles (double-headed arrows). A second axis, also in the femur, is oriented parallel, proximal, and anterior to the primary femoral axis and is termed the *secondary femoral axis about which the patella flexes and extends* (transverse magenta line)[3]. A third axis, in the tibia, is oriented perpendicular to both the primary and the secondary femoral axis and is termed the *longitudinal tibial axis about which the tibia internally and externally rotates on the femur* (vertical orange lines)[3,7]. The oblique yellow line simulates the change in the joint line resulting from external rotation of the femoral component in a valgus knee because of the assumption that the lateral femoral condyle is hypoplastic. External rotation of the femoral component alters the kinematics of the knee.

asymmetry might be necessary when aligning and designing the femoral component.

In this report, we describe a magnetic resonance imaging method for orienting the scanning plane so that both condyles are imaged in a plane perpendicular to the primary femoral axis of the knee about which the tibia flexes and extends. The purpose of the study was to test the hypothesis that the asymmetry between the radii of the medial and lateral femoral condyles in varus and valgus knees with osteoarthritis is small enough to be clinically unimportant.

Materials and Methods

Two hundred and thirty-nine consecutive subjects who had had a total knee arthroplasty for the treatment of primary osteoarthritis of the knee between June 2007 and April 2008 at the same institution and had had a preoperative sagittal magnetic resonance imaging scan of the knee for computer-assisted surgery were considered for inclusion in the study. An institutional review board approved the review of demographic data, radiographs, and magnetic resonance imaging studies.

Whether a patient met the inclusion and exclusion criteria was determined on the basis of a review of the location and extent of cartilage wear and wear of the subchondral bone on the magnetic resonance image of the knee. Subjects were included if cartilage wear was confined to one femoral condyle without wear of the subchondral bone. Patients were excluded (forty in total) when there was wear of the subchondral bone of a femoral condyle (twenty-eight patients), loss of cartilage from both femoral condyles (six), or a primary diagnosis of patellofemoral arthritis with no varus or valgus deformity (six). A congenital longitudinal deficiency of the lower extremity such as an absent fibula, which is known to cause a hypoplastic lateral femoral condyle[8], was a reason for exclusion but was not found in any patient.

The assignment of a knee to the varus or valgus group was based on a review of standing radiographs of the knee in full extension and in 45° of flexion as well as the magnetic resonance imaging scan. Varus knees had medial joint-space narrowing on the radiographs and medial wear on the magnetic resonance imaging scan. Valgus knees had lateral joint-space narrowing on the radiographs and lateral wear on the magnetic resonance imaging scan. The study consisted of 155 varus knees and forty-four valgus knees.

An oblique sagittal magnetic resonance imaging scan of the treated knee was obtained with a 1.5-T scanner and a dedicated knee coil (General Electric Medical Systems, Milwaukee, Wisconsin). The plane for the nonorthogonal, sagittal scan was based on the use of coronal and axial localizer images that projected the femoral condyles in approximately the same plane as that in which the tibia flexes and extends about the femur. Coronal, axial, and sagittal high-resolution localizer images were obtained with a 4-mm slice thickness, a 1-mm spacing/gap, a 256 × 224 matrix, one excitation, and a 24-cm field of view that yielded nine slices in all three planes. The localizer image in the coronal plane that represented the largest projection of the distal femoral condyles was used to adjust the varus-valgus orientation of the plane of the nonorthogonal, sagittal scan. The intersection of the nonorthogonal, sagittal scan plane and the coronal plane was aligned perpendicular to a line connecting the corticocancellous bone interface of the distal femoral condyles (see Appendix). The localizer image in the axial plane that represented the largest projection of the posterior femoral condyles was used to adjust the axial rotation of the plane of the nonorthogonal, sagittal scan. The intersection of the nonorthogonal, sagittal scan plane and the axial plane was aligned perpendicular to a line connecting the corticocancellous bone interface of the posterior femoral condyles (see Appendix). Because the contour of the posterior femoral condyles from 10° to 160° has a single radius of curvature and a single axis[9], and because the tibial-femoral axis of the femur about which the tibia flexes and extends is equidistant from the distal and posterior articular surfaces of the femoral condyles[5], the femoral condyles are projected as both circular in the nonorthogonal, sagittal imaging plane and perpendicular to the tibial-femoral axis of the femur about which the tibia flexes and extends. A two-dimensional, nonorthogonal, sagittal scan was then acquired with use of the following parameters: fast-relaxation fast-spin-echo proton density, 30 to 35-msec echo time, 2800 to 3400-msec repetition time, 31.25-Hz bandwidth, a minimum of two excitations with use of a 16-cm field of view centered at the joint line of the knee, 256 × 224 matrix, 2-mm slice thickness, and no spacing/gap. The length of each side of a pixel of the oblique sagittal image was 0.31 mm.

The radii of the femoral condyles were determined with use of a circle-fitting technique in which the femoral condyle was assumed to have a single radius of curvature from 10° to 160°[5,6,9]. The femoral condyle was magnified two to three times, and the radii of the four adjacent images representing the largest curvature of the medial and lateral femoral condyles were calculated from an overlay of the best-fit circle with image-analysis software (OsiriX, version 3.3.2; http://www.osirix-viewer.com)[10-12] (Fig. 2). The average of the radii on the four adjacent images was considered to be the radius of the condyle.

To determine the clinical varus or valgus angulation, the coronal alignment of the knee was measured preoperatively with a 30.5-cm-long goniometer while the patient was supine and non-weight-bearing.

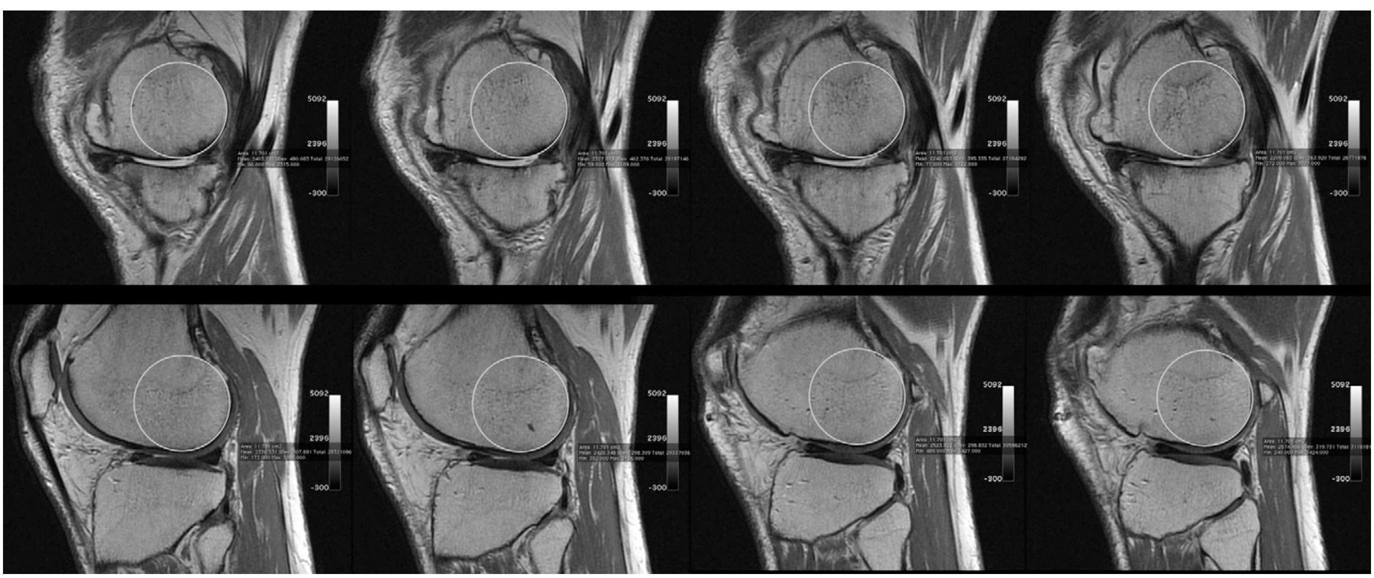

Fig. 2

The method for overlaying a best-fit circle (white circles) to the subchondral-cancellous bone interface of the femoral condyle is shown for a varus knee. In the top row are overlays of the best-fit circle from 10° to 160° on the four adjacent images showing the largest projection of the medial femoral condyle. In the bottom row are the overlays on the lateral femoral condyle. A software tool calculated the area of each circle from which the radius was determined[12]. The radius of a condyle was the average of the radii on the four adjacent images.

TABLE I Patient Demographics*

	Varus Knees (N = 155)	Valgus Knees (N = 44)	Excluded Knees (N = 40)
Age† *(yr)*	68 ± 8.9[a]	69 ± 9.4[a]	70 ± 10.4[a]
F/M *(%)*	62/38[a]	79/21[b]	55/45[a,c]
Height† *(cm)*	169.4 ± 10.9[a]	167.9 ± 9.6[a]	171.4 ± 11.7[a]
Weight† *(kg)*	88.9 ± 17.2[a]	80.7 ± 18.1[b]	86.6 ± 19.5[a,b]
Body-mass index† *(kg/m²)*	31.0 ± 5.3[a]	28.5 ± 4.9[b]	29.6 ± 6[a,b]
White *(%)*	87	93	97
Black *(%)*	3	2	0
Hispanic *(%)*	5	5	3
Asian *(%)*	5	0	0

*In each row, different superscript letters indicate a significant difference ($p < 0.05$). †The values are given as the mean and standard deviation.

Statistical Methods

The arithmetic mean, standard deviation, and 95% confidence interval were used to describe the radii and demographic data. An analysis of variance determined whether the ages, heights, weights, and body-mass indices of the subjects differed among the varus, valgus, and excluded groups. A chi-square goodness-of-fit test determined whether the distribution of women and men differed among the groups. A paired Student t test determined whether the radii of the medial and lateral femoral condyles differed between the varus and valgus knees. Simple linear regressions determined the strength of a variety of associations. The interobserver variability was expressed as the difference between two observers with regard to their measurements of the radii of the medial and lateral condyles on twenty-two randomly selected magnetic resonance images. The level of significance was set at $p < 0.05$.

Source of Funding

There was no external funding source for this study.

Results

On the basis of the number of subjects studied, there was no significant difference in age or height between the varus and valgus groups (Table I). The subjects' weight and body-mass index in the varus group were significantly greater than those in the valgus group ($p < 0.05$). The proportion of men in the varus group was significantly greater than that in the valgus group ($p = 0.036$).

In the group of 155 varus knees, the radius of the lateral condyle was an average of 0.1 mm larger than that of the medial condyle ($p = 0.003$) (Table II). In the group of forty-four valgus knees, the radius of the lateral condyle was an average of 0.2 mm larger than that of the medial condyle ($p < 0.006$).

There was a strong association between the radii of the lateral and medial femoral condyles in the varus ($r^2 = 0.9210$, $p < 0.0001$) and valgus ($r^2 = 0.9129$, $p < 0.0001$) knees (Fig. 3). There was a moderate association between patient height and the radii of the medial ($r = 0.6946$, $p < 0.0001$) and lateral ($r = 0.7009$, $p < 0.0001$) femoral condyles. There was a weak association between patient weight and the radii of the medial ($r = 0.5241$, $p < 0.0001$) and lateral ($r = 0.4954$, $p < 0.0001$) femoral condyles. There was a negligible association between body-mass index and the radii of the medial ($r = 0.0888$, $p = 0.2087$) and lateral ($r = 0.0412$, $p = 0.5544$) femoral condyles. There was a negligible association between the clinical varus/valgus angulation of the knee and the difference between the radii of the lateral and medial femoral condyles ($r = 0.0435$, $p = 0.0471$).

The interobserver variability of the two observers averaged 0.02 mm with a 95% confidence interval of 0.04 to −0.08

TABLE II Radii of the Medial and Lateral Femoral Condyles in Varus and Valgus Knees

Deformity of Osteoarthritic Knee	Radius of Lateral Femoral Condyle* *(mm)*	Radius of Medial Femoral Condyle* *(mm)*	Difference Between Radii (Lateral − Medial) *(mm)*	Significance	Correlation Coefficient
Varus (n = 155)	19.5 ± 2.0	19.4 ± 2.0	0.1	$p = 0.003$	$r^2 = 0.9210$
Valgus (n = 44)	19.9 ± 1.8	19.7 ± 1.7	0.2	$p < 0.006$	$r^2 = 0.9129$

*The values are given as the mean and standard deviation.

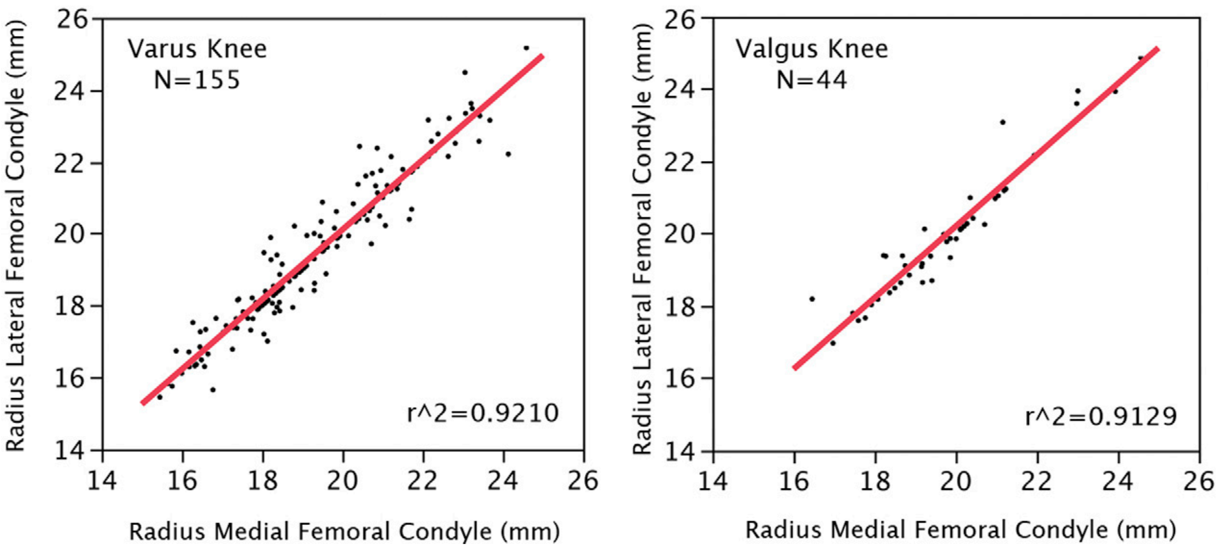

Fig. 3

Scatterplots of the linear regression analysis comparing the radius of the medial femoral condyle with that of the lateral femoral condyle. On the left is the scatterplot for the varus knees. On the right is the scatterplot for the valgus knees.

mm for the measurements of the radii of the medial condyles and −0.04 mm with a 95% confidence interval from 0.02 to −0.1 mm for measurements of the radii of the lateral condyles.

The clinical varus/valgus angulation of the knees (and standard deviation) averaged 1.4° ± 9° of valgus and ranged widely from 30° of valgus to 20° of varus.

Discussion

Because an understanding of the relationship between the radii of the medial and lateral femoral condyles in varus and valgus knees is important for aligning the femoral component and for restoring kinematics in total knee arthroplasty, we used a new method of projecting the femoral condyles perpendicular to the primary femoral axis of the knee to assess the difference between the radii of the medial and lateral femoral condyles in varus and valgus knees with end-stage osteoarthritis. The two principal findings in this study are that the asymmetry between the radii of the medial and lateral femoral condyles is small (≤0.2 mm), and the association between the radii of the medial and lateral femoral condyles is strong, in both varus and valgus knees.

Several limitations of this study might affect the generalization of our finding that the asymmetry between the radii of the medial and lateral femoral condyles is small in varus and valgus knees. First, the evaluation of a relatively small number of valgus knees (forty-four) with a maximum deformity of 30° instead of a larger number of valgus knees with greater deformity might have affected the magnitude of the asymmetry. Second, the asymmetry measured in the Western population of patients in the present study might differ from that in an Asian population, which has a higher prevalence of varus knees[13].

Accurate positioning of the femoral component of a total knee prosthesis is difficult for even the most experienced arthroplasty surgeon because arthritis distorts the surface of the knee, soft tissues conceal the articular surfaces, and conventional and navigation instruments lack precision[14-17]. The ≤0.2 mm of asymmetry between the radii of the lateral and medial femoral condyles can be considered clinically unimportant in total knee arthroplasty because it is relatively small compared with the cumulative error of positioning of the femoral component in six degrees of freedom.

There are diametrically opposed opinions regarding whether a knee has a constant or a shifting axis of rotation and whether the curvature of the condyles is constant (that is, has a single radius) or varies (that is, has multiple radii)[1,7,11,12,18,19]. The description of a shifting axis of rotation and a femoral condyle composed of curves of multiple radii has been based on the use of orthogonal, sagittal lateral radiographs and magnetic resonance images made with no attempt to orient or standardize the projection of the femoral condyles in a plane perpendicular to the primary femoral axis about which the tibia flexes and extends[11,12,18-23]. The radii that govern knee kinematics can be ascertained only by measuring radii in a plane perpendicular to the primary femoral axis[3,5-7,9]. The biplanar localizer images used in the present study selected a nonorthogonal, sagittal imaging plane that was (1) perpendicular to a line connecting the corticocancellous interfaces of the distal parts of the femoral condyles, (2) perpendicular to a line connecting the corticocancellous interfaces of the posterior parts of the femoral condyles, and (3) perpendicular to the primary femoral axis, which, according to previous studies, projects the femoral condyles so that the calculation of the radii reflects the kinematics of the knee[5-7,9]. Therefore, it is the projection from which the femoral condyles are viewed that allows the coexistence of a constant and shifting axis of rotation and a single radius and multiple radii of curvature in the same knee.

The small asymmetry between the radii of the medial and lateral femoral condyles has led us to question the method for setting the rotation of the femoral component in a valgus knee. External rotation of the femoral component has been recommended for valgus knees, to compensate for "hypoplasia" of the lateral femoral condyle and thereby avoid internal rotation and reduce the risk of patellofemoral complications[12,24]. The present study showed, from a kinematic perspective, that the lateral femoral condyle is not hypoplastic with respect to the medial femoral condyle in a valgus knee. Coaligning the primary axis of the femoral component with the primary femoral axis is the sine qua non for restoring normal kinematics[5-7,25-27]. The routine step of externally rotating the femoral condyle in a valgus knee alters the kinematics from normal[5,6] (Fig. 1). Further study is required to determine the effect of the abnormal kinematics on the clinical outcome of total knee arthroplasty.

It is unlikely that varus or valgus wear is caused by a difference between the radii of the femoral condyles. This study showed a small asymmetry between the femoral condyles and a strong association between the radii of the condyles in a given knee. Other causes of varus or valgus wear include relative proximal or distal translation of one femoral condyle with respect to the other (for example, proximal translation of the lateral femoral condyle results in a valgus femur), variability in the longitudinal shape or bowing of the femur and tibia in the coronal plane[28], and variability of the angle formed by the joint line with respect to the mechanical and anatomic axes of the femur and tibia.

Of the demographic data, only patient height was moderately associated with the radii. Height accounted for approximately 49% ($r^2 = 0.49$) of the subject-to-subject variation in radii, which means that another factor or other factors have an equal role in accounting for the variation in the radii. The high prevalence of overweight patients (37% with a body-mass index of 25 to 30 kg/m^2) and obese patients (48% with a body-mass index of >30 kg/m^2) in the present study meant that some subjects weighed the same but had different radii. Therefore, the associations between weight and body-mass index and the radii of the medial and lateral femoral condyles were poor and negligible, respectively.

This relatively large series of biplanar, rotationally controlled magnetic resonance imaging scans of subjects with end-stage osteoarthritis did not show any clinically important asymmetry between the radii of the medial and lateral femoral condyles in either the varus or valgus knees. The clinically unimportant asymmetry and the importance of the radii in defining the primary femoral axis about which the tibia flexes and extends have design and alignment implications for total knee arthroplasty.

Appendix

eA Figures showing the coronal and axial localizer scout images are available with the electronic version of this article on our web site at jbjs.org (go to the article citation and click on "Supporting Data"). ■

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