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Three-dimensional Morphology of the Knee Reveals Ethnic Differences

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Abstract

Background Studies have demonstrated sex differences in femoral shape and quadriceps angle raising a question of whether implant design should be sex-specific. Much of this research has addressed shape differences within the Caucasian population and little is known about differences among ethnic groups.

Questions/purposes We therefore asked: Do shape differences in the distal femur and proximal tibia exist among different ethnic groups and between the sexes in each ethnic population? And if ethnic differences exist, do they have a clinical impact on current TKA design?

Subjects and Methods We analyzed 1000 normal adult knees (80 African American, 80 East Asian, and 860 Caucasian). Three-dimensional surface models were created for each bone and added to three-dimensional statistical bone atlases. Statistical shape analysis was conducted with a process combining principal components and multiple discriminate analyses. Eleven femoral and nine tibial measurements were calculated.

Results We found differences in mean measurements between the sexes and ethnicities. Males had larger knees, with a mean 5-mm-larger anteroposterior dimension than females in all ethnicities. African American females had a 7.4-mm-deeper patellar groove, 2.3-mm-smaller tibial mediolateral dimension, and 2.5-mm-larger tibial anteroposterior dimension than Caucasian females. African American males had a 4.3-mm-larger femoral anteroposterior dimension, 10.1-mm-larger tibial mediolateral dimension, and 6-mm-larger tibial anteroposterior dimension than Asian males.

Conclusions We identified differences in three-dimensional knee morphology among Caucasian, African American, and East Asian populations. Clinical studies will be required to determine whether these differences are important for implant design.

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Introduction

In recent years, many studies have identified shape differences in the knee within the Caucasian population [2, 6, 10]. Shape analyses have identified sex differences in the femoral midshaft, distal femur, and patella [7, 15, 24]. Using automated three-dimensional (3D) morphologic analysis, differences in knee morphology between the sexes has been identified [17, 18]. Differences among European Caucasian males and females have been reported, with females having a smaller mediolateral to anteroposterior ratio and more narrow distal femurs; however, the study suggested morphotype in addition to sex contributed to the distal femur and proximal tibia geometry [2].

Ethnic differences have not received much focus given that most existing TKA implant designs are based on the Caucasian population. Many studies have reported the anatomy and comparison of East Asian populations (Japanese, Chinese, Indian) to existing implant systems [3, 4, 10, 11, 21–23, 26]. Anatomic differences have been identified between both sex and ethnicity, with Caucasian subjects having a higher tibial torsion angle and lower varus alignment than Japanese [12]. Also, females had smaller medial and lateral tibial widths and higher valgus alignment. General size differences have been reported between Chinese and Caucasian knees, with Chinese knees having smaller mediolateral and anteroposterior femoral measurements, tibial measurements, and femoral and tibial aspect ratios, suggesting existing femoral implant designs may not properly accommodate the East Asian population [27]. However, most of these studies focusing on Asians lacked true 3D measurements [20]. Images captured by two-dimensional (2D) methods, such as radiography, provide only a projection of bone shape and do not provide a complete picture of the patient's anatomy. Anatomic landmarks can often be hidden from view and manual measurements calculated using such images can contain interobserver error. Measurements from radiographs are also prone to errors generated from the misalignment of the knee relative to the imaging plane. A 3D analysis can eliminate this error by automatically calculating these measurements in 3D space, more accurately reflecting a person's true anatomy.

We therefore asked: (1) Do shape differences in the distal femur and proximal tibia exist among different ethnic groups? (2) Do shape differences in the distal femur and proximal tibia exist between the sexes in each ethnic population? And (3) if ethnical differences in the shape and size of the distal femur and proximal tibia exist, do they have a clinical impact on current TKA design?

Subjects and Methods

We analyzed 1000 adult knees (840 Caucasians [500 male (CM), 340 female (CF)], 80 African Americans [40 male (AAM), 40 female (AAF)], 80 East Asians [40 male (AM), 40 female (AF)]). All Caucasians were of European descent. CT datasets were obtained through either the William M. Bass Donated Skeletal Collection in the Department of Anthropology or cadaver scans in the Center for Musculoskeletal Research, both at the University of Tennessee, and MRI datasets were obtained through The Osteoarthritis Initiative. We included only normal, nonpathologic bones in this analysis and specifically excluded those with any abnormalities. MRI scans for the 34 AAFs and the 80 East Asians were obtained with 0.36- × 0.36- × 0.69-mm cubic voxels. In addition, 886 CT datasets (840 Caucasians,

Fig. 1 A diagram illustrates the overall process of bone atlas creation. Twelve separate statistical atlases of femora and tibiae were generated for Caucasians, African Americans, and East Asians divided into male and female.
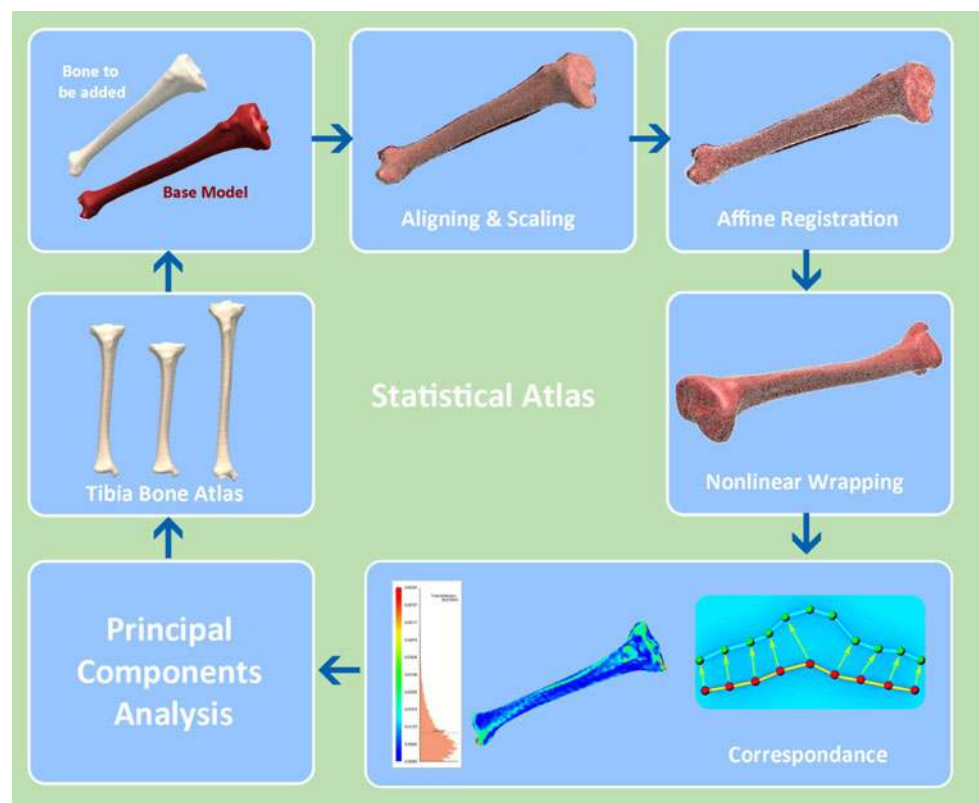
40 AAMs, six AAFs) were acquired with 0.625- × 0.625- × 0.625-mm cubic voxels. DICOM images for both CT and MRI were manually segmented and surface models were generated. This segmentation process has been proven reliable with an interobserver error of 0.163 mm, intraobserver error of 0.105 mm, and pairwise interobserver variability of 0.269 mm [18].

Segmented models for each femur and tibia were added to the bone atlas [18] (Fig. 1). Briefly, a bone atlas is an average model that captures the primary shape variation of a bone and allows for the comparison of global shape differences between groups or populations, guaranteeing standardization, normalization, and landmark correspondence across a population. Twelve separate statistical atlases of femora and tibiae were generated for Caucasians, African Americans, and East Asians divided into male and female.

To fully identify shape differences among ethnicities, a two-step feature extraction methodology was implemented (Fig. 2). The first step identified global shape differences between the sexes in each ethnicity and between the sexes across all ethnicities. This method utilized principle component analysis [13], a mathematical tool that reduces the dimensionality of variables while maintaining most of the variance of the original data, both as a means of variable reduction and as a global shape descriptor. This method finds points of high discrimination between different sex and ethnic groups when normalized against the first principal component, which is considered primarily scale,
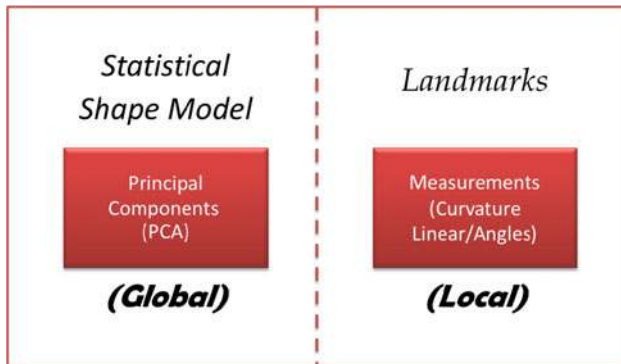

Fig. 2 A diagram illustrates the two-step feature extraction methodology implemented to fully identify shape differences among ethnicities. PCA = principal component analysis.
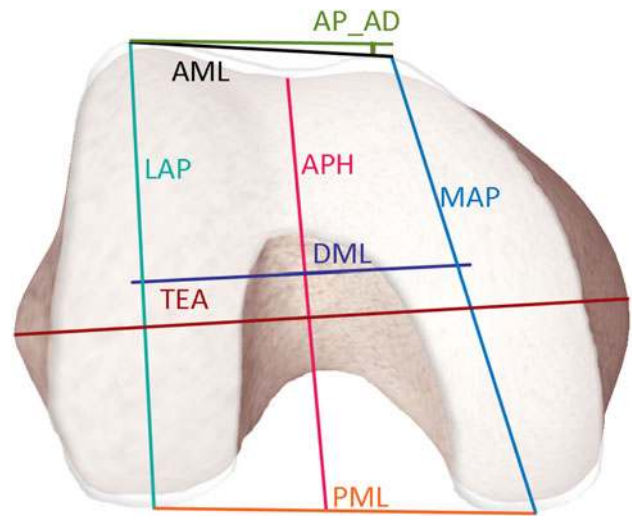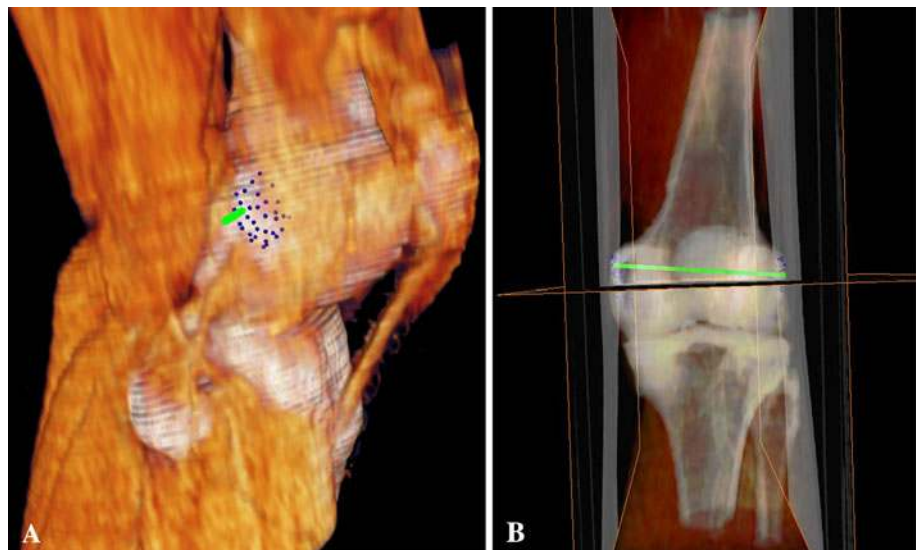

Fig. 4 A diagram illustrates measurements on the distal femur. TEA = transepicondylar axis length; APH = anteroposterior height; MAP = medial anteroposterior height; LAP = lateral anteroposterior height; AP_AD = anteroposterior angle difference; AML = anterior mediolateral length; PML = posterior mediolateral length; DML = distal mediolateral length.

Fig. 3A–B An example shows the advantage of our 3D method when calculating the transepicondylar axis. (A) A volume rendering of the knee shows the transepicondylar axis passing through a series of points collected on the epicondyles. (B) An image shows the automatically calculated transepicondylar axis and a sample image slice to demonstrate the axis does not lie in one CT slice; thus, localizing directly on the CT image will produce rotational error.
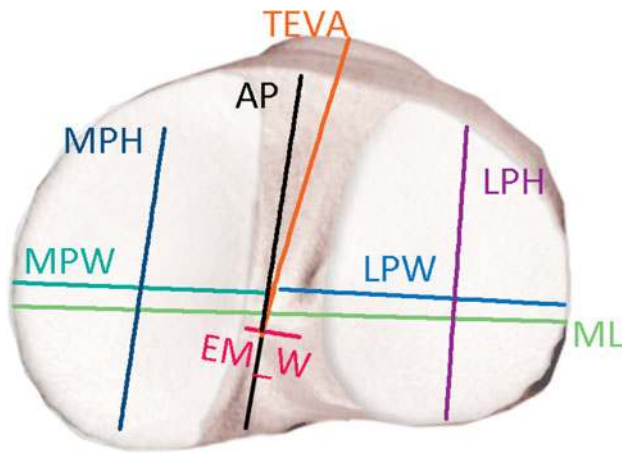
Fig. 5 A diagram illustrates measurements on the proximal tibia. ML = mediolateral width; AP = anteroposterior height; EM_W = eminence width; TEVA = tuberosity eminence vector angle; LPW = lateral plateau mediolateral width; LPH = lateral plateau anteroposterior height; MPW = medial plateau mediolateral width; MPH = medial plateau anteroposterior height.

highlighting areas that would be highly discriminating without the use of any other information. This algorithm was used to examine shape differences independent of size differences between the sexes and among the three ethnicity populations. The second step utilized anatomic and surgical landmarks to automatically calculate linear measurements, angular measurements, and curvature once each bone was added to the atlas.

Three-dimensional landmarks were automatically calculated on each bone [18]. Landmarks sometimes falling between CT slices can be miscalculated in 2D analyses. Utilizing a 3D approach ensures all landmarks are anatomically accurate in three dimensions (Fig. 3). Using these landmarks, a set of linear and angular measurements was calculated on the distal femur (Fig. 4) and proximal tibia (Fig. 5). In total, 11 femoral (Table 1) and nine tibial (Table 2) measurements were recorded.

Using the above measurements, three normalized ratios that best describe femoral shape were calculated: mediolateral width/anteroposterior height (ML/AP), anterior mediolateral length/posterior mediolateral length (AML/PML), and medial anteroposterior height/lateral anteroposterior height (MAP/LAP). These ratios were used to classify and describe the shapes of femora: Type I and II with regard to ML/AP, Type III and IV based on AML/PML, and Type V and VI based on LAP/MAP (Fig. 6). Type I femurs are more square in shape with a ML/AP

Table 1. Measurement definitions for the distal femur

Measurement	Definition
Transepicondylar axis length	Distance between medial and lateral epicondyles
Anteroposterior height	Distance between anterior cortex points and the posterior plane
Medial anteroposterior height	Distance between most anterior and posterior aspects of the medial condyle
Lateral anteroposterior height	Distance between most anterior and posterior aspects of the lateral condyle
Anatomic axis-distal axis angle	Angle between anatomic axis and axis connecting the two most distal points of the medial and lateral condyles
Patellar groove height	Distance between aspect of the intercondylar notch and the midpoint between the two most distal points on the medial and lateral condyles
Anteroposterior angle difference	Angle of the vector connecting the two most anterior points on the lateral and medial condyles and the vector relative to the posterior plane
Anterior mediolateral length	Distance between the two most anterior aspects of the medial and lateral condyles
Posterior mediolateral length	Distance between the two most posterior aspects of the medial and lateral condyles
Distal mediolateral length	Distance between the two most distal aspects of the medial and lateral condyles
Condylar twist angle	Angle between the transepicondylar axis and posterior condylar axis

Table 2. Measurement definitions for the proximal tibia

Measurement	Definition
Mediolateral width	Maximum width of the tibia plateau in the mediolateral direction
Anteroposterior height	Length of the tibial plateau in the anteroposterior direction, passing through the midpoint of the tibial intercondylar eminence
Eminence mediolateral ratio	Medial plateau mediolateral width to mediolateral width ratio
Eminence width	Distance between medial and lateral intercondylar eminence points
Tuberosity eminence vector angle	Angle between anteroposterior direction and a line connecting the intercondylar eminence midpoint and tibial tuberosity
Lateral plateau mediolateral width	Length of the lateral tibial plateau in the mediolateral direction
Lateral plateau anteroposterior height	Length of the lateral tibial plateau in the anteroposterior direction
Medial plateau mediolateral width	Length of the medial tibial plateau in the mediolateral direction
Medial plateau anteroposterior height	Length of the medial tibial plateau in the anteroposterior direction

closer to 1 whereas Type II femurs have a higher ratio and are more rectangular in shape. Type III femurs are more triangular with a smaller AML/PML ratio whereas Type IV
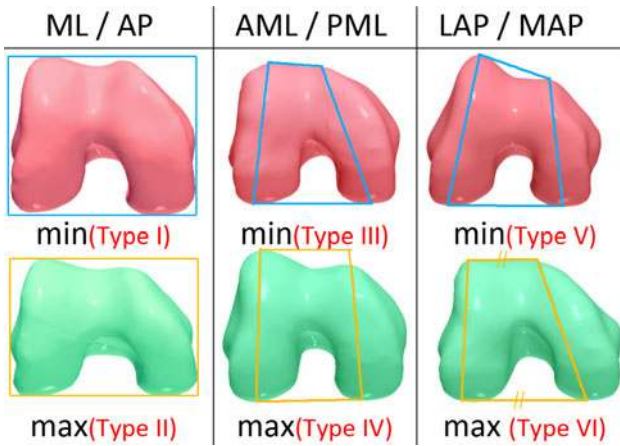

Fig. 6 A diagram illustrates the six classifications used to describe femoral shape based on three normalized ratios. Type I and Type II classify femoral shape relative to mediolateral width/anteroposterior height (ML/AP), Type III and Type IV classify femoral shape relative to anterior mediolateral length/posterior mediolateral length (AML/PML), and Type V and Type VI classify femoral shape relative to medial anteroposterior height/lateral anteroposterior height (MAP/LAP).

femurs are more rectangular. A smaller MAP/LAP ratio implies a lesser angle between the anterior and posterior condylar axes, indicating a Type V femur, whereas the anterior and posterior condylar axes are more parallel to one another in Type VI femurs. Three ratios were also calculated on the tibia: ML/AP, lateral plateau width/lateral plateau height (LPW/LPH), and medial plateau width/medial plateau height (MPW/MPH).

Curvature of the femoral condyle and tibial plateau are integral in dictating normal knee motion as curvature of the lateral and medial condyles is one of the main factors affecting knee kinematics. In general, a more curved knee has a higher ROM. To accurately map, and therefore analyze, the femoral condyle curvature, three profiles were used to approximate the most prominent contact points on both the medial and lateral sides and the patellar groove. The medial profile was calculated by defining a plane that passes through the most anterior, distal, and posterior points on the medial condyle. This plane was then intersected with the distal femur and the resulting contour was resampled into 50 equidistance points. This profile contour represented the most protruding points on the medial condyle surface. Similarly, the same method was used to calculate the lateral profile. To accurately calculate the curvature of the sulcus, a set of contours were extracted by intersecting the distal
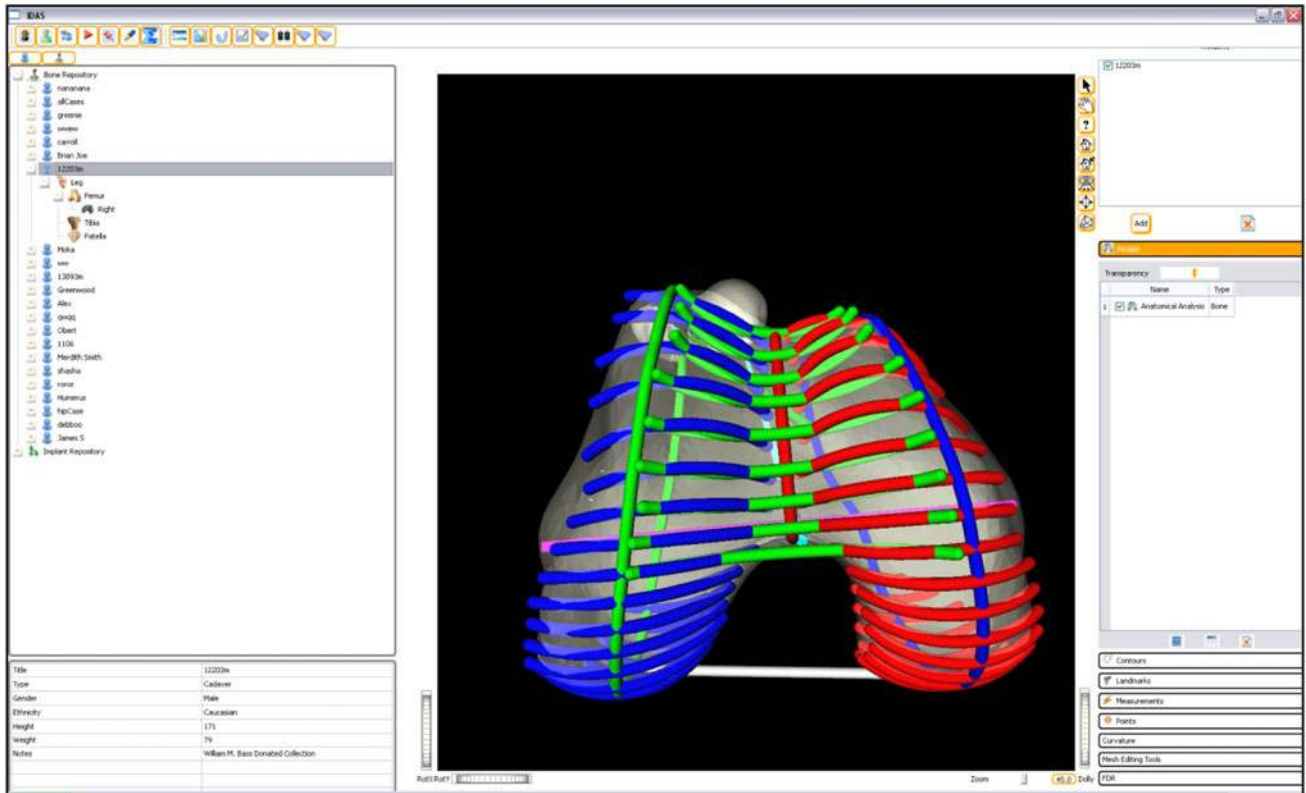

Fig. 7 Mapping of the distal femoral curvature shows the medial, lateral, and groove profiles.

femur with a series of planes rotating around the transepicondylar axis in 10° increments. The lowest points on these contours were then used to define the sulcus points (Fig. 7). To quantify curvature of the medial and lateral condyles and sulcus profiles, an iterative least-square algorithm was developed to break down each curve into a number of radii of curvature that best approximated that curve.

Differences in the sex and ethnic group means of femoral measurements, femoral curvature, and tibia measurements were tested by one-way ANOVA and t test. Due to the imbalanced sample size, two versions of the t test for both equal and unequal variance were utilized. Hypothesis of equal variance was tested using f test. The power test was used to calculate the minimum sample size required to test the null hypothesis of two populations from different means. Discriminate analysis, a means of determining discrimination between two or more groups, was used along with principal component analysis to rank bone surfaces using statistics captured from populations using IDAS software [16]. ANOVA, t test, f test, and power test

Table 3. Femoral linear and curvature measurements

Parameter	African American				Caucasian				East Asian			
	Male		Female		Male		Female		Male		Female	
	Mean	SD	Mean	SD	Mean	SD	Mean	SD	Mean	SD	Mean	SD
TEA (mm)	84.9	4.7	76.8	4.9	85.9	4.7	75.8	3.3	85.4	4.3	74.8	3.3
AP (mm)	61.2	2.9	57.4	8.3	61.2	3.6	55.9	3.3	54.9	4.4	50	4
ML/AP	1.39	0.07	1.38	0.34	1.41	0.06	1.36	0.06	1.56	0.11	1.5	0.1
MAP (mm)	66.9	3.5	63.9	6.5	65.7	3.7	59.4	3.3	62.6	3.8	56.4	3
LAP (mm)	71.1	3.5	64.1	4.9	67.8	4.1	61.4	3.2	64.8	4.4	57.8	3.2
AADAA (°)	97.98	2.11	92.31	13.1	99.07	1.84	99.9	1.98	97.96	8.01	101.74	5.99
GH (mm)	7.5	1.6	13.6	8.5	6.8	1.7	6.3	1.8	7.8	2.2	7.4	2.6
AP_AD (°)	7.88	3.34	5.26	3.02	6.55	3.43	6.91	2.8	5.13	2.8	5.2	1.97
AML (mm)	38.1	3.6	31.1	6	34.4	3.5	29.9	2.9	37	2.9	31.8	2.3
PML (mm)	52.1	5.1	46.7	4	53.5	4.2	46.9	2.9	50.9	5	44.8	3.3
DML (mm)	55	4.5	48.9	4.7	54.4	4.3	47.2	3.5	48.8	4	43.6	2.9
CTA (°)	5.09	2.37	6.19	2.02	5.29	3.1	5.99	3.12	5.16	1.65	6.22	1.63
AML/PML	0.74	0.08	0.67	0.14	0.64	0.07	0.64	0.06	0.73	0.07	0.71	0.05
MAP/LAP	0.94	0.04	1	0.07	0.97	0.04	0.97	0.03	0.97	0.03	0.98	0.03
M_C1 (mm)	23.2	4.1	19.6	3.9	32.8	62.5	27.5	65.6	18.4	1.5	16.2	1.8
M_C2 (mm)	34.9	9	35.6	19	39	23.4	36.7	12.1	50.5	9.1	51.3	7.1
M_C3 (mm)	85.9	94.8	90.1	150.5	56.8	56.1	59.9	82.9	24.9	3.5	20.3	2.6
M_C4 (mm)	29.2	5.6	34.1	20.1	41.9	60.1	37.6	58.9	NA	NA	NA	NA
M_L1 (mm)	19.6	1	18.1	2.3	21.6	6.8	19.2	6.2	17.7	1.3	15.9	0.9
M_L2 (mm)	21.6	1.1	20.2	2.6	23.2	5.8	20.8	5.6	44.6	3.2	40	2.2
M_L3 (mm)	25.6	1.3	23.3	3.2	27.8	7.7	24.9	7.2	16.9	1.2	15.2	0.8
M_L4 (mm)	18.7	1	17.4	2.3	20.2	5.6	18.2	5.5	NA	NA	NA	NA
L_C1 (mm)	24.5	3.2	21.6	2.9	22.8	2.7	21.1	2.7	21.9	2.5	20.9	1.9
L_C2 (mm)	38.1	7.3	29.8	4.2	35.9	8.4	31.4	4.4	37.7	5.8	32.5	2
L_C3 (mm)	48.5	37.2	39.4	14.6	43.5	13.3	49.9	27.7	28.7	8.8	32.2	39.8
L_C4 (mm)	35.9	17.3	80.2	122.4	35.4	16.7	31.1	21.3	NA	NA	NA	NA
L_L1 (mm)	18.9	1	18.8	2.9	18.5	1.1	16.7	0.9	17.7	0.8	16.4	0.8
L_L2 (mm)	20.9	1.1	20.7	3.2	20.5	1.3	18.4	1	44.4	2.1	41.3	2.1
L_L3 (mm)	24.7	1.3	24.4	3.7	24.2	1.5	21.8	1.2	16.8	0.8	15.6	0.8
L_L4 (mm)	18	0.9	17.8	3	17.6	1.1	15.8	0.9	NA	NA	NA	NA

TEA = transepicondylar axis length; AP = anteroposterior height; ML = mediolateral width; MAP = medial anteroposterior height; LAP = lateral anteroposterior height; AADAA = anatomic axis-distal axis angle; GH = patellar groove height; AP_AD = anteroposterior angle difference; AML = anterior mediolateral length; PML = posterior mediolateral length; DML = distal mediolateral length; CTA = condylar twist angle; M_C1–C4 = medial profile radii of curvature where C1 is anterior and C4 is posterior; M_L1–L4 = medial profile arc length where L1 is anterior and L4 is posterior; L_C1–C4 = lateral profile radii of curvature where C1 is anterior and C4 is posterior; L_L1–L4 = lateral profile arc length where L1 is anterior and L4 is posterior; NA = not available.

Table 4. Tibial linear measurements

Parameter	African American				Caucasian				East Asian			
	Male		Female		Male		Female		Male		Female	
	Mean	SD	Mean	SD	Mean	SD	Mean	SD	Mean	SD	Mean	SD
ML (mm)	79.3	3.8	66.2	3.8	79.2	4.6	68.6	4.8	68.3	8.6	68	3
AP (mm)	57.3	3.7	52.5	3.8	56.8	3.5	50	3.8	51.3	3.8	48.1	3.3
ML/AP	1.39	0.07	1.26	0.08	1.4	0.06	1.37	0.09	1.33	0.12	1.42	0.1
EM_MLR	0.48	0.05	0.74	0.11	0.48	0.03	0.48	0.05	0.63	0.11	0.58	0.06
EM_W (mm)	11.3	3.7	5.5	4.6	12	4.3	10.3	5	7	4.4	10.2	2.4
TEVA (°)	121.98	5.88	107.53	9.57	124.3	5.42	123.33	7.89	117.79	8.33	115.9	8.09
LPW (mm)	28.4	2.5	25.5	1.4	27.6	1.9	24.2	1.8	26.4	2.5	22.4	1.3
LPH (mm)	23	2.4	23	1.7	22	1.7	19.3	1.9	18.5	1.9	16	1.5
MPW (mm)	34.5	2.9	36.9	3.5	35.5	2.9	30.8	3.5	33.6	3.7	29.4	1.8
MPH (mm)	21	4.3	30.4	6.3	22.6	2.7	19.4	3.4	22.6	1.7	20.3	0.9
LPW/MPW	0.83	0.09	0.7	0.05	0.78	0.05	0.81	0.35	0.79	0.06	0.76	0.04
LPH/MPH	1.16	0.37	0.8	0.24	0.99	0.18	1.07	0.56	0.82	0.09	0.79	0.08

ML = mediolateral width; AP = anteroposterior height; EM_MLR = eminence mediolateral ratio; EM_W = eminence width; TEVA = tuberosity eminence vector angle; LPW = lateral plateau mediolateral width; LPH = lateral plateau anteroposterior height; MPW = medial plateau mediolateral width; MPH = medial plateau anteroposterior height.

calculations were completed using MATLAB® (The MathWorks, Inc, Natick, MA USA).

Results

Shape differences among the ethnic groups were identified in the distal femur (Table 3) and proximal tibia (Table 4). On examining femoral differences among ethnicities, medial and lateral curves for African Americans and Caucasians were best approximated using four radii of curvature, C1 to C4, whereas East Asians were best approximated using three, C1 to C3 (Fig. 8). AAMs and AAFs had larger ($p < 0.01$) AP dimensions than their Asian and Caucasian counterparts and AMs and AFs had smaller ($p < 0.01$) AP dimensions than CMs and CFs. When compared to CFs with similar AP dimensions, AMs had larger ($p < 0.01$) ML dimensions. In analyzing ethnic differences in tibial anatomy, AAMs had larger ($p < 0.01$) LAPs and smaller MPHs than CMs, while also having larger ($p < 0.01$) ML and AP dimensions than AMs. AMs and AFs had smaller ($p < 0.01$) ML and AP dimensions than CMs and CFs. Figure 9 outlines areas of high (red) and low (blue) morphologic differences in both the femur and tibia captured by the second to ninth principal components among sex and ethnicity. These femoral linear (Table 5), femoral curvature (Table 6), and tibial (Table 7) differences were highlighted in the t tests and power tests based on the automated measurements. Several of these measurements directly correlated to some of the shape differences found in the femur and tibia (Fig. 10).
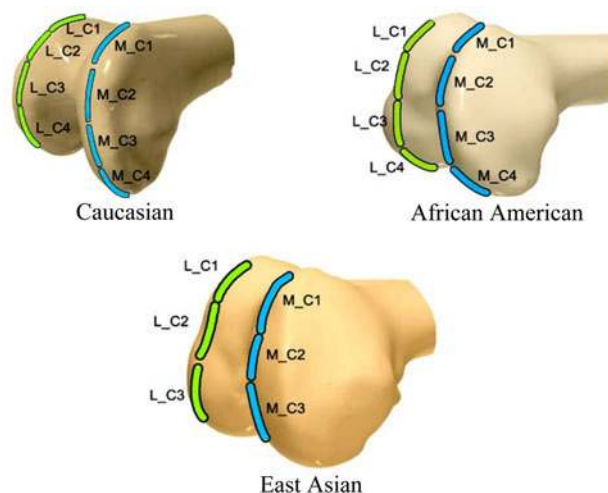

Fig. 8 Images show approximation of distal femoral curvature of the lateral and medial profiles using four radii of curvature for Caucasians and African Americans and three radii of curvature for East Asians.

Shape differences in the distal femur and proximal tibia were identified between sexes in each ethnic population. Males across all ethnicities had average 9-mm larger ($p < 0.01$) ML and 5-mm larger ($p < 0.01$) AP dimensions than their female counterparts. AAMs and CFs had shallower ($p < 0.01$) patellar grooves than AAFs and CMs. Females had more curved ($p < 0.01$) femurs in all ethnicities. Males had larger ($p < 0.01$) tibial AP dimensions than females. AAMs and CMs had larger ($p < 0.01$) ML dimensions than AAFs and CFs, respectively. Differences in femoral (Table 8) and tibial (Table 9) shapes were
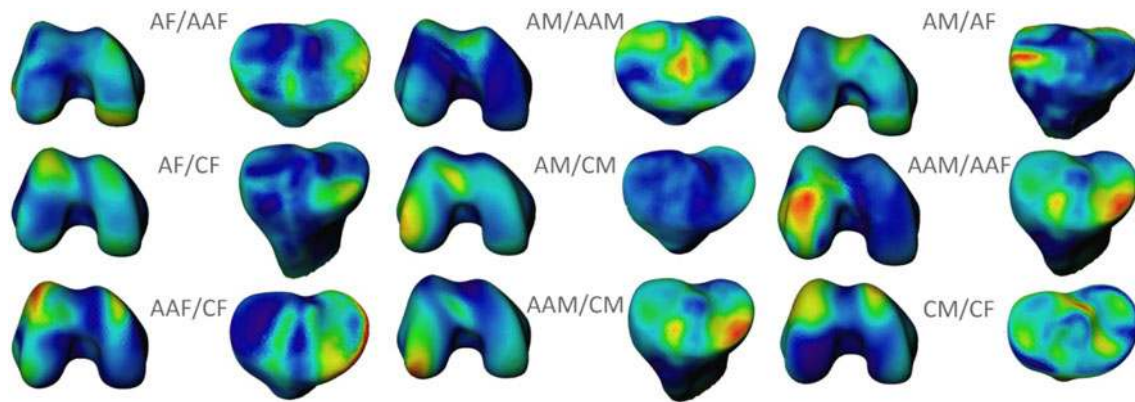
Fig. 9 Images illustrate the comparison of high (red) and low (blue) global shape differences among sex and ethnicity groups captured by the second to ninth principal components. AM = East Asian male; AF = East Asian female; CM = Caucasian male; CF = Caucasian female; AAM = African American male; AAF = African American female.

identified in comparing shapes across populations based on differences in ML/AP, AML/PML, and MAP/LAP ratios.

The morphologic differences identified among the ethnicities in this study indicated notable clinical implications on existing TKA design. For example, the AP of AMs (54.9 ± 4.4 mm) was similar to that of CFs (55.9 ± 3.3 mm), which could lead to the wrongful assumption of using sex-specific implants for AMs. However, a closer look reveals substantial ML and ML/AP ratio differences between these two groups, which could lead to underhang when using such implants for AMs. When comparing datasets with the same AP (57.4 mm), we found AMs (ML = 85.6 mm) had a 6-mm-larger ML than CFs (ML = 80 mm). Likewise, another comparison of datasets (AP = 49.7 mm) showed AMs (77 mm) had a 6-mm-larger ML than comparable CFs (ML = 71 mm).

Discussion

Ethnic differences have not received much focus given that most research has been aimed at the investigation of shape differences within the Caucasian population [2–4, 6, 10, 11, 17, 21–23]; however, previous studies have reported the anatomy and comparison of East Asian populations (Japanese, Chinese, Indian) to existing implant systems [3, 4, 10, 11, 21–23, 26]. We therefore asked: (1) Do shape differences in the distal femur and proximal tibia exist among different ethnic groups? (2) Do shape differences in the distal femur and proximal tibia exist between the sexes in each ethnic population? And (3) if ethnic differences in the shape and size of the distal femur and proximal tibia exist, do they have a clinical impact on current TKA design?

There are a number of limitations to our study. First, while we found statistically significant differences in the size and morphology of the distal femur and proximal tibia

in sex and ethnicity, further investigation is required to closer examine any clinical impact of each of these differences. While a direct comparison of the absolute and average values revealed a difference of a few millimeters, it is the analysis of different aspect ratios that has clinical relevance with a combined impact on both shape and size. Second, our Caucasian population was much larger than the African American and East Asian (consisting mainly of Chinese, Korean, and a few Japanese subjects) populations and thus we utilized two versions of the t test for both equal and unequal variance. Third, we did not investigate the tibial slope as this measurement is calculated relative to the tibial mechanical axis. Some of our datasets included only the proximal tibia preventing proper calculation of the mechanical axis. Lastly, the measurements recorded from the bone models analyzed in this study did not contain hyaline cartilage. Two studies suggest the thickness of the articular cartilage in the knee follows the surface topography of the subchondral bone [5, 9]; therefore, measurements of the sagittal radii can be extrapolated from the bone measurements. The actual thickness of the articular cartilage is variable, with the thickest cartilage being central on the femoral condyle in the weightbearing region and the thinnest along the periphery in regions of less weightbearing. Hence, it is safe to assume the shape and dimension of the distal femur and proximal tibia measured along the periphery are impacted little by the thickness of the articular cartilage.

We identified ethnic differences among the three populations examined. We found AMs had a smaller ML/AP ratio than CMs (1.33 ± 0.12 versus 1.4 ± 0.06), contrary to Yue et al. [27] who reported a larger tibial aspect ratio in Chinese men compared to Caucasian men (1.82 ± 0.07 versus 1.75 ± 0.11). Our mean and SD values of the ML for CMs (79 ± 4.6 mm) and CFs (68.6 ± 4.8 mm) were comparable to those published by Yue et al. [27] who

Table 5. Comparison of linear femoral measurements between sexes and ethnicities

Compared groups	Test	TEA (mm)	AP (mm)	ML/AP	MAP (mm)	LAP (mm)	AADAA (°)	GH (mm)
AM/AF	t test	0.01*	0.01*	0.02*	0.01*	0.01*	0.03	0.49
	p test	4	20	76	9	8	90	854
	Diff	−10.64	−4.91	−0.06	−6.19	−6.99	3.78	−0.42
AAM/AAF	t test	0.01*	0.02*	0.88	0.03	0.01*	0.05	0.01*
	p test	10	58	†	88	11	74	21
	Diff	−8.07	−3.77	−0.01	−2.75	−6.79	−4.06	5.53
CM/CF	t test	0.01*	0.01*	0.01*	0.01*	0.01*	0.01*	0.01*
	p test	5	11	48	8	9	138	302
	Diff	−10.08	−5.33	−0.05	−6.36	−6.36	0.83	−0.50
AAM/CM	t test	0.20	0.88	0.13	0.06	0.01*	0.01*	0.01*
	p test	612	†	474	256	40	86	125
	Diff	0.99	0.09	0.01	−1.16	−3.14	1.10	−0.75
AAF/CF	t test	0.25	0.29	0.74	0.01*	0.01*	0.01*	0.01*
	p test	421	362	2702	28	54	34	15
	Diff	−1.02	−1.55	−0.02	−4.79	−2.84	5.99	−6.77
AAM/AM	t test	0.65	0.01*	0.01*	0.01*	0.01*	0.99	0.51
	p test	2143	9	7	19	11	†	1077
	Diff	0.50	−6.31	0.17	−4.30	−6.30	−0.02	0.30
AAF/AF	t test	0.03	0.01*	0.57	0.01*	0.01*	0.01*	0.01*
	p test	95	41	1010	11	11	27	21
	Diff	−2.12	−5.82	0.05	−7.52	−6.32	9.43	−6.24
AM/CM	t test	0.59	0.01*	0.01*	0.01*	0.01*	0.46	0.02*
	p test	2161	11	8	39	53	513	92
	Diff	0.50	6.32	−0.16	3.13	3.03	1.11	−1.03
AF/CF	t test	0.08	0.01*	0.01*	0.01*	0.01*	0.08	0.02*
	p test	252	10	9	30	20	123	96
	Diff	1.06	5.90	−0.14	2.96	3.66	−1.84	−1.12
AM/CF	t test	0.01*	0.26	0.01*	0.01*	0.01*	0.20	0.01*
	p test	5	396	5	32	35	173	44
	Diff	−9.58	0.99	−0.20	−3.24	−3.33	1.94	−1.54

Compared groups	Test	AP_AD (°)	AML (mm)	PML (mm)	DML (mm)	CTA (°)	AML/PML	MAP/LAP
AM/AF	t test	0.91	0.01*	0.01*	0.01*	0.01*	0.22	0.24
	p test	†	7	12	12	63	276	300
	Diff	0.07	−5.13	−6.13	−5.28	1.05	−0.02	0.01
AAM/AAF	t test	0.01*	0.01*	0.01*	0.01*	0.05	0.02*	0.01*
	p test	41	12	20	16	120	70	23
	Diff	−2.57	−7.19	−5.30	−6.04	1.03	−0.07	0.06
CM/CF	t test	0.20	0.01*	0.01*	0.01*	0.02*	0.29	0.16
	p test	1886	14	8	8	519	2641	1604
	Diff	0.37	−4.47	−6.60	−7.21	0.70	−0.01	0.00
AAM/CM	t test	0.03*	0.01*	0.10	0.40	0.77	0.01*	0.01*
	p test	195	25	284	1449	†	20	50
	Diff	−1.25	−3.75	1.43	−0.60	0.12	−0.09	0.03
AAF/CF	t test	0.01*	0.34	0.86	0.05	0.74	0.27	0.01*
	p test	87	498	†	144	8749	355	60
	Diff	1.60	−1.03	0.13	−1.77	−0.14	−0.03	−0.03

Table 5. continued

Compared groups	Test	AP_AD (°)	AML (mm)	PML (mm)	DML (mm)	CTA (°)	AML/PML	MAP/LAP
AAM/AM	t test	0.01*	0.16	0.34	0.01*	0.88	0.73	0.01*
	p test	33	214	483	13	†	3676	50
	Diff	−2.75	−1.14	−1.17	−6.20	0.07	−0.01	0.03
AAF/AF	t test	0.93	0.48	0.04	0.01	0.94	0.12	0.09
	p test	†	787	101	14	†	149	140
	Diff	−0.06	0.76	−1.87	−5.33	0.03	0.04	−0.02
AM/CM	t test	0.03	0.01*	0.01*	0.01*	0.72	0.01*	0.69
	p test	126	39	81	15	9421	18	3894
	Diff	1.42	−2.61	2.61	5.60	0.12	−0.09	0.00
AF/CF	t test	0.01*	0.01*	0.01*	0.01*	0.52	0.01*	0.05
	p test	51	47	55	20	2710	16	193
	Diff	1.71	−1.95	2.14	3.67	−0.23	−0.07	−0.01
AM/CF	t test	0.01*	0.01*	0.01*	0.03*	0.04	0.01*	0.85
	p test	64	5	26	144	219	14	†
	Diff	1.78	−7.09	−3.99	−1.61	0.82	−0.09	0.00

* Significant difference; †result greater than 10,000 samples; TEA = transepicondylar axis length; AP = anteroposterior height; ML = mediolateral width; MAP = medial anteroposterior height; LAP = lateral anteroposterior height; AADAA = anatomic axis-distal axis angle; GH = patellar groove height; AP_AD = anteroposterior angle difference; AML = anterior mediolateral length; PML = posterior mediolateral length; DML = distal mediolateral length; CTA = condylar twist angle; AM = Asian male; AF = Asian female; AAM = African American male; AAF = African American female; CM = Caucasian male; CF = Caucasian female; p = power; diff = difference.

Table 6. Comparison of femoral curvature measurements between sexes and ethnicities

Compared groups	Test	M_C1	M_C2	M_C3	M_C4	M_L1	M_L2	M_L3	M_L4	L_C1	L_C2	L_C3	L_C4	L_L1	L_L2	L_L3	L_L4
AM/AF	t test	0.01*	0.68	0.01*	NA	0.01*	0.01*	0.01*	NA	0.05	0.01*	0.61	NA	0.01*	0.01*	0.01*	NA
	p test	15	2542	12	NA	10	10	10	NA	107	15	1277	NA	13	13	12	NA
AAM/AAF	t test	0.01*	0.84	0.89	0.16	0.01*	0.01*	0.01*	0.01*	0.01*	0.01*	0.14	0.04	0.81	0.83	0.69	0.66
	p test	33	†	†	177	30	42	27	44	27	13	214	65	6522	7862	2386	1943
CM/CF	t test	0.37	0.13	0.67	0.44	0.01*	0.01*	0.01*	0.01*	0.01*	0.01*	0.01*	0.02*	0.01*	0.01*	0.01*	0.01*
	p test	3676	1464	†	4830	198	153	172	205	62	53	262	495	9	9	9	9
AAM/CM	t test	0.01*	0.05	0.14	0.01*	0.01*	0.01*	0.01*	0.01*	0.01*	0.18	0.36	0.62	0.04*	0.04*	0.04*	0.03*
	p test	328	487	420	178	110	127	113	117	101	477	574	4081	201	200	201	178
AAF/CF	t test	0.13	0.75	0.25	0.55	0.07	0.27	0.05	0.17	0.35	0.05	0.01*	0.02*	0.01*	0.01*	0.01*	0.01*
	p test	505	5533	388	3475	370	955	300	626	918	185	106	56	22	21	22	27

* Significant difference; †result greater than 10,000 samples; M_C1–C4 = medial profile radii of curvature where C1 is anterior and C4 is posterior; M_L1–L4 = medial profile arc length where L1 is anterior and L4 is posterior; L_C1–C4 = lateral profile radii of curvature where C1 is anterior and C4 is posterior; L_L1–L4 = lateral profile arc length where L1 is anterior and L4 is posterior; AM = Asian male; AF = Asian female; AAM = African American male; AAF = African American female; CM = Caucasian male; CF = Caucasian female; p = power; NA = not available.

recorded 69 ± 4.2 mm for CFs and 78.7 ± 5 mm for CMs; however, the authors contradicted their finding in the conclusion by reporting Chinese men have wider proximal tibiae than CMs. In addition, our normalized ratios and nonlinear shape analysis supported differences between East Asians and Caucasians independent of any scale factor. We found differences in the ratio between AAF/CF and AAM/CM, with the mean ratio being larger in CMs compared to AAMs and CFs compared to AAFs. This finding conflicts with Gillespie et al. [8] who reported a larger ML/AP ratio in African Americans than in Caucasians; however, their African American population was from the early 20th century, which could account for differing anatomic features from the current population. The radii of curvature analysis on both the medial and lateral condyles revealed AMs and AFs tend to have more curved

Table 7. Comparison of tibial linear measurements between sexes and ethnicities

Compared groups	Test	ML (mm)	AP (mm)	ML/AP	EM_MLR	EM_W (mm)	TEVA (°)	LPW (mm)	LPH (mm)	MPW (mm)	MPH (mm)	LPW/LPH	MPW/MPH
AM/AF	t test	0.88	0.01*	0.01*	0.03	0.01*	0.35	0.01*	0.01*	0.01*	0.01*	0.40	0.04
	p test	†	33	40	79	29	488	6	12	12	9	594	86
	Diff	−0.25	−3.16	0.09	−0.05	3.23	−1.90	−4.01	−2.51	−4.19	−2.25	−0.02	−0.04
AAM/AAF	t test	0.01*	0.01*	0.01*	0.01*	0.01*	0.01*	0.01*	0.93	0.01*	0.01*	0.01*	0.01*
	p test	3	17	11	3	13	8	13	†	47	9	16	17
	Diff	−13.08	−4.77	−0.12	0.26	−5.84	−14.45	−2.89	0.04	2.39	9.48	−0.13	−0.47
CM/CF	t test	0.01*	0.01*	0.01*	0.89	0.01*	0.17	0.01*	0.01*	0.01*	0.01*	0.62	0.1
	p test	6	8	264	†	189	1239	8	12	13	22	†	838
	Diff	−10.66	−6.77	−0.02	0.00	−1.73	−0.96	−3.43	−2.73	−4.68	−3.29	0.00	0.05
AAM/CM	t test	0.92	0.36	0.40	0.34	0.33	0.01*	0.06	0.02*	0.05	0.02*	0.60	0.06
	p test	†	1115	1081	719	834	155	199	116	231	114	2338	147
	Diff	−0.08	−0.55	0.01	0.01	0.71	2.32	−0.81	−0.95	0.97	1.67	0.01	−0.14
AAF/CF	t test	0.01*	0.01*	0.01*	0.01*	0.01*	0.01*	0.01*	0.01*	0.01*	0.01*	0.01*	0.01*
	p test	88	58	15	3	26	8	36	7	9	5	10	19
	Diff	2.34	−2.55	0.11	−0.25	4.82	15.80	−1.35	−3.73	−6.11	−11.09	0.15	0.37
AAM/AM	t test	0.01*	0.01*	0.02*	0.01*	0.01*	0.02*	0.01*	0.01*	0.23	0.04	0.01*	0.01*
	p test	9	11	74	7	23	75	41	6	312	92	13	31
	Diff	−11.05	−6.04	−0.06	0.16	−4.31	−4.19	−2.02	−4.45	−0.95	1.60	0.19	−0.25
AAF/AF	t test	0.03*	0.01*	0.01*	0.01*	0.01*	0.01*	0.01*	0.01*	0.01*	0.01*	0.01*	0.01*
	p test	96	17	9	9	14	29	5	2	4	4	3	24
	Diff	1.78	−4.42	0.15	−0.16	4.76	8.36	−3.13	−7.00	−7.53	−10.13	0.29	0.18
AM/CM	t test	0.01*	0.01*	0.01*	0.01*	0.01*	0.01*	0.01*	0.01*	0.01*	0.82	0.01*	0.01*
	p test	10	12	45	7	20	30	87	7	75	†	10	59
	Diff	10.97	5.49	0.07	−0.15	5.01	6.50	1.21	3.50	1.92	0.08	−0.17	0.1
AF/CF	t test	0.38	0.01*	0.01*	0.01*	0.92	0.01*	0.01*	0.01*	0.01*	0.01*	0.01*	0.01*
	p test	1269	93	118	9	†	31	20	8	92	126	15	29
	Diff	0.56	1.87	−0.04	−0.10	0.06	7.43	1.78	3.27	1.42	−0.96	−0.15	0.19
AM/CF	t test	0.85	0.09	0.06	0.01*	0.01*	0.01*	0.01*	0.05	0.01*	0.01*	0.01*	0.01*
	p test	†	227	138	8	53	56	24	160	44	16	13	52
	Diff	0.31	−1.28	0.04	−0.15	3.29	5.54	−2.22	0.77	−2.76	−3.21	−0.17	0.15

*Significant difference; †result greater than 10,000 samples; ML = mediolateral width; AP = anteroposterior height; EM_MLR = eminence mediolateral ratio; EM_W = eminence width; TEVA = tuberosity eminence vector angle; LPW = lateral plateau mediolateral width; LPH = lateral plateau anteroposterior height; MPW = medial plateau mediolateral width; MPH = medial plateau anteroposterior height; AM = Asian male; AF = Asian female; AAM = African American male; AAF = African American female; CM = Caucasian male; CF = Caucasian female; p = power; diff = difference.

condyles (ie, less radius of curvature) than Caucasians, implying a larger ROM. This finding agrees with Leszko et al. [14] who found an increased ROM of 153° for AF and 151° for AM compared to 146° for CM.

We observed sex differences in each of the populations analyzed. Women from all ethnic groups had smaller, narrower knees with a smaller ML/AP ratio. These results are comparable to those reported in other studies [2, 8]. Although a number of studies have published results of sex differences, we find it difficult to compare measurements as each method utilized is different. Three-dimensional modeling of the distal femur and proximal tibia from CT and MRI has the advantage of obtaining the full shape of both bones, as well as obtaining the anatomic coordinate axes and rotational landmarks. Direct measurements during surgery and bone wafer measurements do not reveal the true shape, provide rotational references, or maintain coordinate axes [10, 25]. In addition, radiographic analysis creates a pattern of variability due to variations in the angle of the xray beam and magnification, not to mention the bone margins may not be representative of the true shape of the distal femur and proximal tibia [19]. However, we did find our MLs for CMs (85.9 ± 4.7 mm) and CFs (75.8 ± 3.3 mm) were comparable to the anthropologic

Fig. 10 Images illustrate the correlation between global shape analysis using principal component analysis and geodesic measurements. TEA = transepicondylar axis length; APH = anteroposterior height; MAP = medial anteroposterior height; LAP = lateral anteroposterior height; AP_AD = anteroposterior angle difference; AML = anterior mediolateral length; PML = posterior mediolateral length; DML = distal mediolateral length.
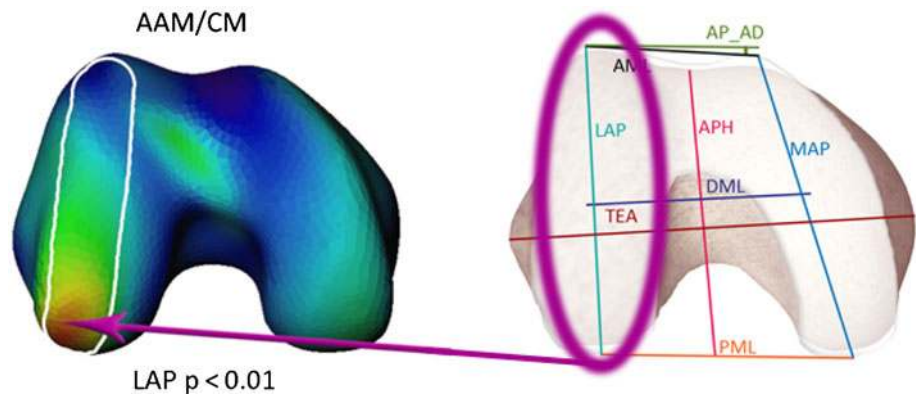

Table 8. Comparison of classification types (I–VI) used to describe femoral shape based on ML/AP, AML/PML, and MAP/LAP ratios*

Compared groups	Classification type
AAM/CM	IV and V
AAF/CF	VI
AAF/AM	I and V
AM/CM	II and IV
AM/CF	II and IV
AAM/AAF	IV and V

* Populations compared in this table only include those with statistically significant ML/AP, AML/PML, or MAP/LAP ratios; ML = mediolateral width; AP = anteroposterior height; AML = anterior medial length; PML = posterior medial length; MAP = medial anteroposterior height; LAP = lateral anteroposterior height; AAM = African American male; CM = Caucasian male; AAF = African American female; CF = Caucasian female; AM = Asian male.

Table 9. Comparison of tibial shapes based on ML/AP ratio*

Compared groups	Tibial shape
AAF/CF	Square
AAF/AF	Square
AAM/AM	Rectangular
AM/CM	Square
AF/CF	Rectangular

* Populations compared in this table only include those with statistically significant ML/AP ratios; ML = mediolateral width; AP = anteroposterior height; AAF = African American female; CF = Caucasian female; AF = Asian female; AAM = African American male; AM = Asian male; CM = Caucasian male.

Fig. 11 A graph shows femoral ML and AP measurements and the regression line for each sex and ethnic group. ML = mediolateral width; AP = anteroposterior height.
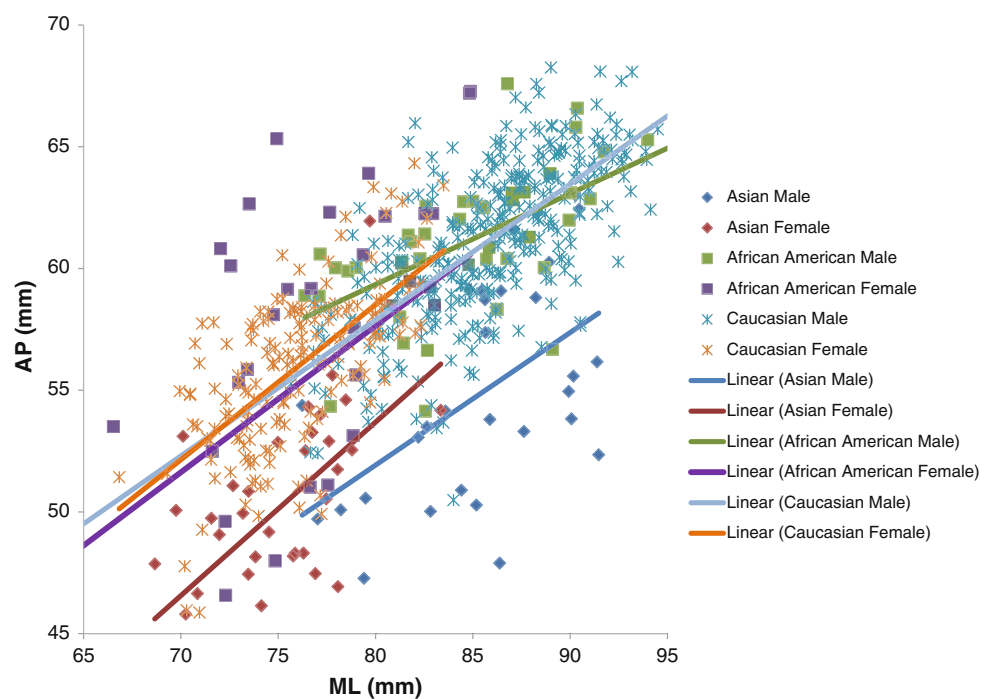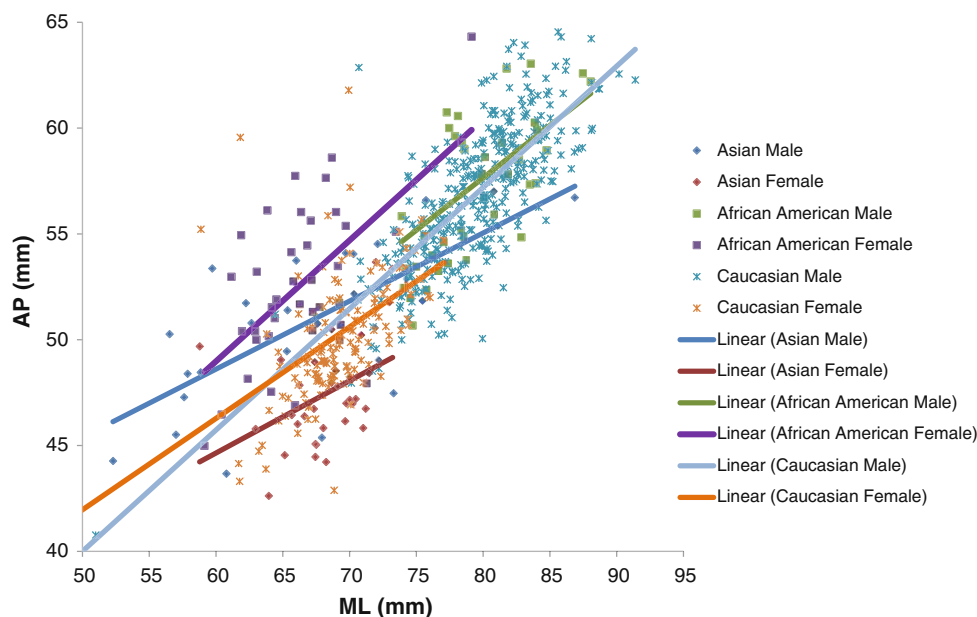
Fig. 12 A graph shows tibial ML and AP measurements and the regression line for each sex and ethnic group. ML = mediolateral width; AP = anteroposterior height.

measurement of bicondylar width taken by Alunni-Perret et al. [1] who recorded 84.3 ± 3.6 mm for CMs and 74.8 ± 2.5 mm for CFs. In addition, we found females tended to have more curved knees and thus higher ROM. This finding agrees with Leszko et al. [14] who measured an average maximum flexion of 152° for CFs and 153° for AFs compared to 146° and 151° for CMs and AMs.

In sizing the femoral component, the AP is important in maintaining the flexion-extension gap, optimizing patellofemoral tracking and tension in the quadriceps mechanism; all of which impact knee motion and stability. In contrast, the ML determines bone coverage and soft tissue tension. Current implant designs and surgical techniques account for morphologic differences by compromises during surgery to fit the average implant on the measured anatomy, avoiding overhang and soft tissue impingement with a larger prosthesis or instability with a smaller prosthesis.

New anatomic and morphologic insights for both the femur (Fig. 11) and tibia (Fig. 12) brought forth in this paper may help foster implant design changes in all component parts in TKA; however, further evaluation is needed to determine whether these design changes would improve clinical outcome. Ethnic differences in the anatomy of the knee have also been identified by this study. Some Asian surgeons claim current knee implants do not fulfill the requirements of their patient population [21]. Further investigation is needed to evaluate any clinical impact of implant designs based on these ethnic differences.

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