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ORIGINAL STUDY

Morphological measurement of the knee : race and sex effects

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Three-dimensional knee models of 148 Chinese (61 males, 87 female) and of 127 Caucasian (79 male, 48 female) were constructed. The anteroposterior (fAP, tAP) and mediolateral (fML, tML) dimensions of cross-section of the femur and tibia after simulated TKA bony resection were measured. Females have smaller femoral aspect ratios (fML/fAP) than males (Chinese : 1.22 ± 0.05 vs 1.29 ± 0.04 ; Caucasians : 1.18 ± 0.05 vs 1.25 ± 0.05) (P < 0.05). The tibial aspect ratios (tML/tAP) of the Chinese males (1.56 ± 0.07) and the Caucasian females (1.54 ± 0.07) are smaller than that of the Caucasian males (1.61 ± 0.08) (P < 0.05). In regression analysis, for the same fAP or tAP dimension, females have narrower femoral condyles or tibia platforms than males ; the Caucasian males have narrower femoral condyle or wider tibial platform than the Chinese males. For the same fAP dimension, males have lager tibial platforms than females ; the Chinese males have larger tibial platforms than the Caucasian males. Racial and sex differences of the resected femur and tibia surfaces were found between a Chinese population and a Caucasian population. The relationship between the femur and tibia also showed racial and sex differences. These results may provide guidelines for future development of sex-specific as well as race-specific total knee replacement surgeries.

INTRODUCTION

In total knee arthroplasty (TKA) area, many studies have indicated that a sex-specific prosthesis may be necessary to better fit the male or female patient knee joint geometry (*8,9,12*). Clarke *et al* (*8*) found that, with traditional unisex prosthesis, the femoral component overhang was observed in 17% of female Caucasian patients, while no overhang was observed in male patients. Further, as the TKA surgeries grow fast in Asian countries (*17*), there is also a growing demand on a race-specific prosthesis that can better fit the patient population of Asian countries (*16,26*).

Several recent studies have reported on the geometric features of the male and female knees (*7,30*) and investigated the morphology of Asian knees (*3,5,13,15,19,20*). Most of these studies have compared the differences between the existing TKA components used in Asian patients and the Asian patient knee geometries, and found that the femoral

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Table I. — Demographic data of the subjects.

	Sex	Subject No	Age (Years)	Weigh (Kg)	Height (cm)
Chinese (CH)	Male Female	61 87	50.6±6.7 43.3±5.6	69.2±7.5 60.9±8.0	171.6±5.1 159.1±4.7
Caucasian (C)	Male Female	79 48	36.8±10.9 35.5±10.1	87.6±17.1 69.7±8.7	179.2±7.7 165.1±4.7

aspect ratio of these prostheses were not suitable for the Asian patients (*3,5,15,19*). Femoral component mismatching has been observed in female patients of Asia-Pacific population (*7,20*). For example, Ha *et al* (*13*) showed that current TKAs do not provide a reasonable fit for small or large Korean knees. Chen *et al* (*5*) found that all sizes of several prostheses were overhang in the medial-lateral direction. Yue *et al* (*29*) reported the racial and sex morphologic differences between a Chinese population and a Caucasian population based on non-resected surfaces of the knee. The morphological measurement data in resected bony surface is directly related to the implant design and surgical planning (*4*). However, there is no report that compared the Caucasian and Asian knees after a general TKA bony resection.

The objective of this study is to investigate the racial and sex morphologic differences of the Chinese and Caucasian knees using 3-dimensional (3D) knee models. The 3D models were prepared to simulate the resected surfaces of the femur and tibia using a standard TKA procedure. Further, we investigated the relationship between the femur and tibia by correlating the dimensions of the femur with those of tibia. We hypothesize that there are distinct racial and sex differences between the Chinese and Caucasian knees ; and the anteroposterior dimension of the femur could be used to predict the other geometric dimensions of the knee.

MATERIALS AND METHODS

Subjects

Total 275 knees of living subjects (148 Chinese, 127 Caucasians) were analyzed in this study (Table I). The subjects were evaluated with no anatomical abnormality, history of knee pain/injury and other knee pathologies.

3-Dimensional Knee Models

The 3D images of the Caucasian (MRI) and Chinese (CT) populations were obtained from two different previous investigations that were approved by the institutional review boards. All Caucasian knees were MRI scanned using a 3.0 Tesla magnet (Siemens, Erlangen, Germany) with a fat suppressed 3D spoiled gradient-recalled sequence. Parallel sagittal plane images of 1 mm in thickness with no space between were obtained with a field of view of 180 mm × 180 mm and an in-plane resolution of 512 × 512 pixels. All Chinese knees were scanned using a CT scanner (GE Medical System, Milwaukee, WIS, USA). The images were acquired along axial direction between the mid shafts of the femur and tibia with a slice thickness of 0.625 mm and an in-plane resolution of 0.3 mm × 0.3 mm. During the CT or MRI scan, the subject was laid in supine with his or her knee in a relaxed extension position.

The 3D bony models of the Chinese knees were segmented using a region-growing method (*1*), and the Caucasian knees using a manual segmentation method (*29*). The segmented contours were then reviewed and manually corrected. Surface models of the distal femur and tibia were reconstructed using the contours. A 3D deviation analysis between MRI and CT knee models of one subject revealed that the average ± standard deviation of the distance in between were -0.39 ± 0.64 mm and -0.38 ± 0.69 mm for the femur and tibia, respectively. A compatible accuracy of MRI models with respect to CT models was reported in a previous study (*24*).

Femoral Morphology

To make simulated TKA cuts, the anatomical axis of the femur was defined along the femoral shaft (Fig. 1A). The mechanical axis was defined as a line 6° valgus with the anatomical axis of the femur in coronal plane (*5*). The femoral epicondylar line was drawn to connect the most apexes of the medial and lateral femoral condyles. The distal femur was cut 7 mm (considering a 2 mm thickness of cartilage (*10*)) above the lowest point of the medi-

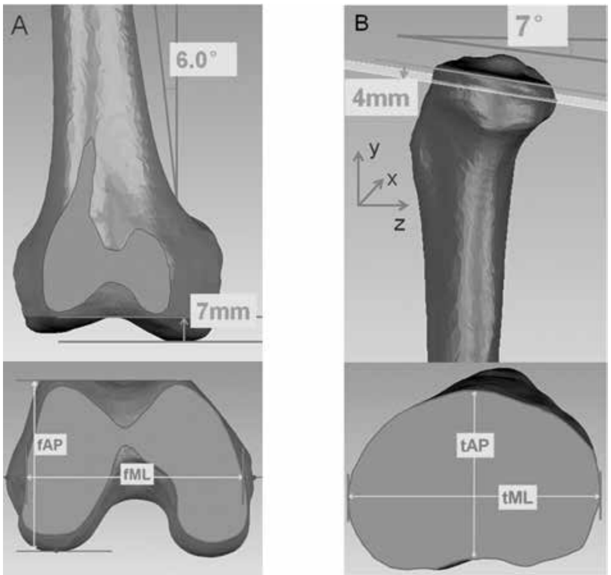

Fig. 1. — The femoral and tibial models and bony cuts to simulate a standard TKA procedure. A 2 mm cartilage thickness was considered in the resection. (A) The distal femur ; and (B) the proximal tibia viewed in frontal and transverse planes.

al condyle. The femoral mediolateral dimension (fML) was the mediolateral measurement of the distal femoral cut surface that is parallel to the femoral epicondylar axis in the transverse plane (*5*). The femoral anteroposterior dimension (fAP) was defined as the distance between the lowest lateral condyle with the lateral anterior cortex of the distal femur (Fig. 1A) that simulated the anterior condyle cut in a standard TKA surgery (*21*).

Tibial Morphology

The tibia mechanical axis was defined as a line along the tibial shaft (Fig. 1B) ; a line that was parallel and collinear to the surgical epicondylar axis of the femur in the transverse plane was defined as the mediolateral axis of the tibia (*25*). The proximal tibia was cut perpendicular to the tibial shaft axis, 4 mm below the medial tibial plateau with (considering a 2 mm thickness of cartilage (*10*)) a posterior slope of 7° (*19*). The tibial mediolateral (tML) dimension was defined as the longest mediolateral line that is parallel to the mediolateral axis on the proximal tibial cut surface. The tibial anteroposterior (tAP) dimension was taken as the length of a line drawn passing through the mid-point of and perpendicular to the tML line (*5*) (Fig. 1B).

Data Analysis

The geometric dimensions measured in this study were anteroposterior lengths (fAP, tAP) and mediolateral widths (fML, tML) of the femur and tibia (*5,14,20*). The femoral aspect ratio (fML/ fAP) and the tibial aspect ratio (tML/ tAP) were calculated to analyze the shape of the knee (*14*).

The data were analyzed in 3 ways. The average dimensions of all subject groups were compared. The dimension data was then examined as functions of the anteroposterior lengths of the femur and tibia (fAP and tAP) through a regression analysis. Because the fAP is widely used as a parameter for implant sizing and strongly associated with normal gait motion and accurate ligamentous balancing in flexion and extension (*11*), we analyzed the correlation of the fAP with the tAP and tML of each knee to examine the relationships between the dimensions of the femur and tibia. The tibiofemoral aspect ratios (tAP/fAP and tML/fAP) representing the shape of the knee were also analyzed.

Statistical analysis

A one-way ANOVA was used to determine if the morphological measurements were statistically different between the races and sexs. A statistical significance is defined when $P < 0.05$. Best-fit lines were calculated using the least-squares regression method (*14*). The Pearson correlation coefficient, *r*, was used to represent the correlation of fAP with other parameters of the tibia. A negative correlation is found when $r < 0.0$ and a positive correlation is found when $r > 0.0$. A negligible correlation is defined when $|r| = 0.0$-0.1 ; a weak correlation when $|r| = 0.1$-0.3 ; a definite correlation when $|r| = 0.3$-0.7 ; and a strong correlation when $|r| = 0.7$-1.0 (*19*).

RESULTS

Distal femoral condyle

The average fAP and fML dimensions of the females were significantly smaller than those of the males (Table II). The fAP and fML dimensions of the Chinese population, either of males or of females, were significantly smaller than those of the Caucasian population (P < 0.05). The fML/fAP ratios of the Chinese and Caucasian females are significantly smaller than those of their respective

Table II. — Morphological data of the femur and tibia (Mean±SD).

	Femur				Tibia			
	fML	fAP	Aspect ratio (fML/fAP)	Correlation coefficient (r)	tML	tAP	Aspect ratio (tML/tAP)	Correlation coefficient (r)
CH-M (range)	72.7± 3.8 (63.3-80.0)	56.5± 2.5 (50.8-61.6)	1.29±0.04 (1.20-1.42)	0.7235 β	77.4± 3.3 (67.3-83.1)	49.6± 2.4 (44.4-54.8)	1.56±0.07 (1.38-1.73)	0.5289 α
CH-FM (range)	64.4± 2.6* (58.2-69.6)	52.8± 2.6* (48.0-59.0)	1.22±0.05* (1.11-1.37)	0.5017 α	69.1± 2.8* (62.6-75.3)	44.2± 2.3* (38.1-48.7)	1.56±0.06 (1.44-1.73)	0.6605 β
C-M (range)	74.6± 3.9 *† (66.0-81.9)	59.6± 3.2*† (52.7-66.7)	1.25±0.05† (1.15-1.36)	0.7292 β	79.4± 4.3*† (66.4-88.4)	49.5± 2.9† (43.0-58.2)	1.61±0.08 (1.40-1.88) *†	0.6548 β
C-FM (range)	65.4± 1.4* † ‡ (62.5-68.9)	55.4± 2.8* † ‡ (50.5-61.3)	1.18±0.05* † ‡ (1.08-1.28)	0.5571 α	70.2± 2.7* † ‡ (66.0-80.0)	45.2± 2.3* † ‡ (40.2-49.6)	1.54±0.07 (1.43-1.67) ‡	0.6151 β

CH-M(Chinese male), CH-FM (Chinese female), C-M(Caucasian male), C-FM(Caucasian female).
* means statistic difference with Chinese male.
† means statistic difference with Chinese female.
‡ means statistic difference with Caucasian male.
α means statistical significance in correlation ($P<0.05$).
β means statistical significance in correlation ($P<0.01$).

males. The Chinese females have a larger fML/fAP ratio than the Caucasian females ($p < 0.05$), but the males of the two populations are not significantly different in the fML/fAP ratio.

For both populations, the fML was found positively correlated with the fAP in all conditions, but the fML/ fAP ratio was found negatively correlated with the fAP in all subject groups (Fig. 2). For the same fAP values along the regression curves (Fig. 2A), both the Chinese and Caucasian females have a smaller fMLs than the males ; the Chinese males have a larger fMLs than the Caucasian males. There were distinct offset between the fML/fAP ratios of the Chinese and Caucasian males, indicating that the Caucasian males have a smaller fML/fAP ratio than the Chinese males (Fig. 2B**)**. Females have narrower femoral condyle than males, and the Caucasian males have narrower femoral condyle than the Chinese males. The Chinese females have larger fML in larger fAP dimensions, but have smaller fML in smaller fAP dimensions than those of the Caucasian females (Fig. 2A).

Proximal tibia

For both populations, the tML was found positively correlated with the tAP, but the tML/tAP ratio was found negatively correlated with the tAP (Fig. 3). Both tAP and tML dimensions of the females were significantly smaller than those of the males (Table II). The tAP and tML dimensions of the Chinese population, either of males or of females, were significantly smaller than those of the Caucasians ($P < 0.05$). The Caucasian females have smaller tML/tAP ratio than the males. The tML/tAP ratios of the Chinese males and females and of the Chinese and Caucasian males are not significantly different (Fig. 3B).

For the same tAP dimension along the regression curves (Fig. 3A), both Chinese and Caucasian females have smaller tMLs than the males ; the Chinese males have smaller tML than the Caucasian males. Because there were distinct offset between the tML/tAP ratios of the Chinese males and females and between the Chinese and Caucasian males ; the Chinese females have a smaller tML/tAP ratio than the males and Chinese males have a smaller tML/tAP ratio than the Caucasian males for the same tAP dimension (Fig. 3B**)**. Females have narrower tibia platform than males, and the Chinese males have narrower tibia platform than the Caucasian males. The differences in tML between the Chinese and Caucasian females are small (Figs. 3A and B).

The Tibiofemoral relation of the knee

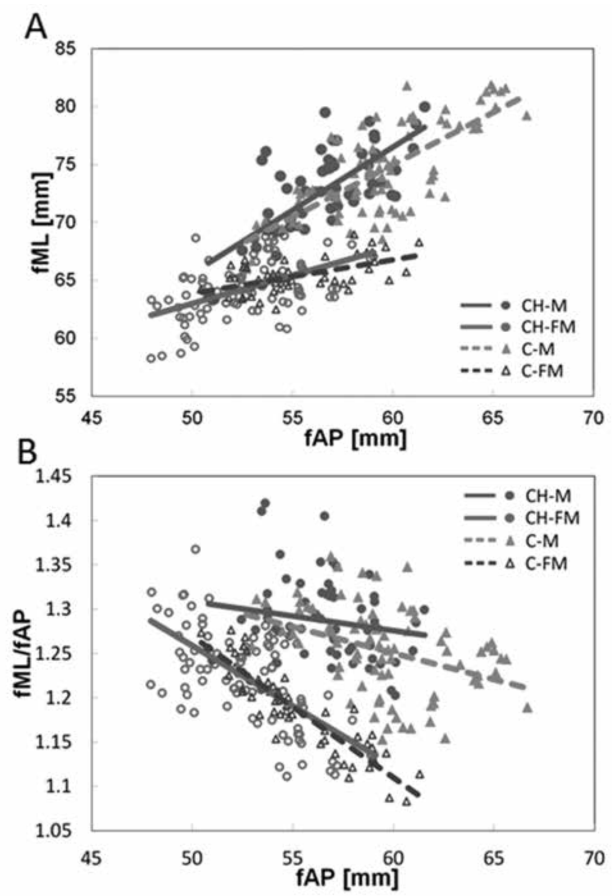

Fig. 2. — Racial and sex effects on the resected distal femur of the Chinese males(CH-M) and females(CH-FM), Caucasian males (C-M) and females(C-FM). (A) fML vs fAP dimensions ; and (B) fML/fAP aspect ratio vs fAP dimension.

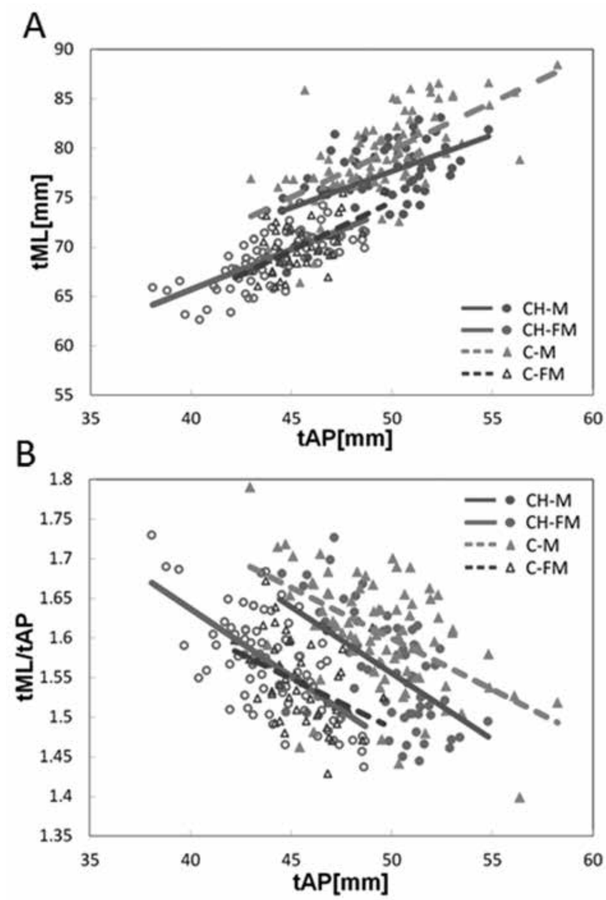

Fig. 3. — Racial and sex effects on the resected proximal tibia of the Chinese males(CH-M) and females(CH-FM), Caucasian males (C-M) and females(C-FM). (A) tML vs tAP dimensions ; and (B) tML/tAP aspect ratio vs tAP dimension.

Both tAP and tML were shown to positively correlated with the fAP for all subject groups ($P < 0.05$) (Table III). The tAP/fAP and tML/fAP ratios are also different for different races and sexes (Figs. 4 and 5).

For the same fAP dimension, both the Chinese and Caucasian males have larger tibial dimensions (both the tAP and tML) than the females, and Chinese males have larger tibial dimensions than the Caucasian males (Figs. 4 and 5). The Chinese females have a larger tAP within the range of small fAP sizes and a smaller tAP within the range of large fAP sizes than the Caucasian females (Fig. 4). The Chinese females have larger tMLs than the Caucasian females under the same fAP (Fig. 5).

DISCUSSION

This study investigated the geometric differences of the knees of a Chinese population and a Caucasian population. The data indicated that in general, Chinese knees are smaller than the Caucasian knees ; and female knees were smaller than male knees. The knee shapes represented using fML/fAP and tML/tAP ratios varied with races and sexes. The females have a narrower femoral condyle and a narrower tibial platform than the males for a given anteroposterior femoral dimen-

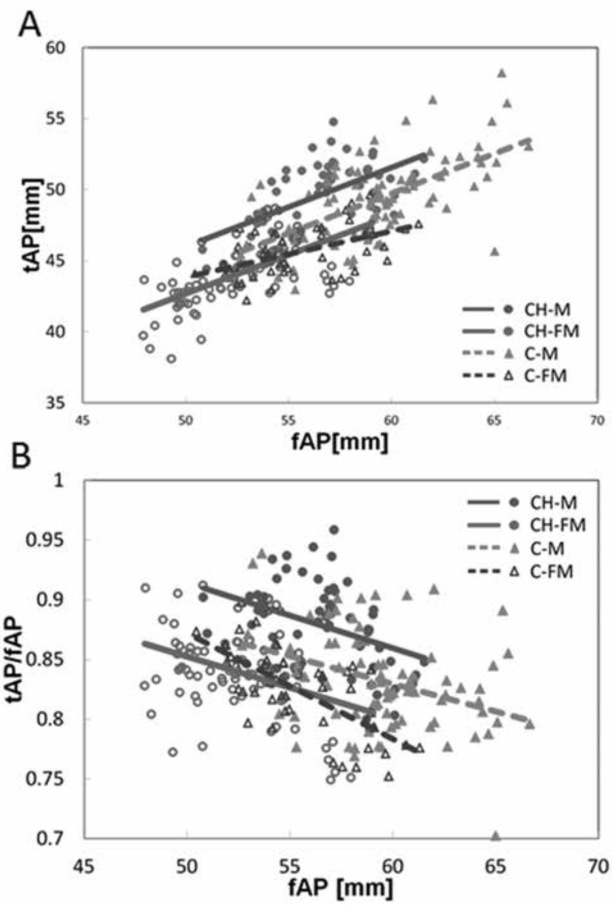

Fig. 4. — Racial and sex effects on the femorotibial morphological relations. (A) The relation of the tibia and femur in anteroposterior dimensions, tAP vs fAP ; B) the aspect ratio (tAP/fAP) vs fAP dimension.

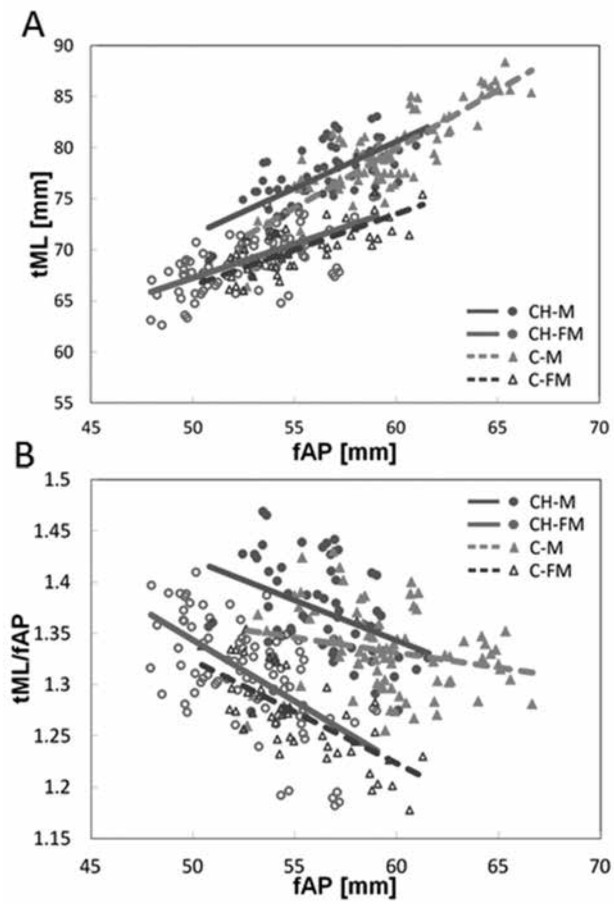

Fig. 5. — Racial and sex effects on the femorotibial morphological relations. (A) The relation of the mediolateral dimension of the tibia with the anteroposterior dimension of the femur, tML vs fAP ; B) the aspect ratio (tML/fAP) vs fAP dimension.

sion (fAP) or tibial dimension (tAP). In the same knee joint, the tibial dimensions are correlated to the anteroposterior dimensions of the femur. For knees with the same fAP, the Caucasian males have a narrower femoral condyle than the Chinese males while the Chinese males have a narrower tibial platform than the Caucasian males.

Several studies have measured the morphology of Asian knees using various methods (Table IV). The anteroposterior dimension of the femur (fAP) of this study is about 10 mm smaller than those of Chen *et al* (*5*) and Ha *et al* (*13*). However, their measurements included the anterior femoral condyle thickness. Our fAP data was about 10 mm larger than that of Kwak *et al* (*18*), but their measurement didn't include the posterior condyle thickness. Their fML data was close to our measurement. *et al* (*21*) reported the fAP and fML which were close to our data on Caucasian subjects. Chin *et al* (*6*) reported average data of males and females, that is similar to the average data of our male and female subjects.

The data on the tibial dimensions (tAP and tML) between our measurements and those reported in literature were inconsistent due to different measurement methods too (Table IV). Ha *et al* (*13*) measured the medial and lateral tAP and showed larger data than our measurements ; Uehara *et al* (*25*) also

Table III. — Correlation of fAP with tAP and tML

	Aspect ratio		Correlation coefficient (r)	
	tAP / fAP	tML / fAP	tAP / fAP	tML / fAP
CH-M	0.88±0.04	1.37±0.05	0.5948 α	0.7019 β
CH-FM	0.84±0.04*	1.31±0.05*	0.6379 β	0.6351 β
C-M	0.83±0.04*	1.33±0.04*†	0.6074 β	0.8511 β
C-FM	0.82±0.04*	1.27±0.04* † ‡	0.5372 α	0.7225 β

CH-M(Chinese male), CH-FM (Chinese female), C-M (Caucasian male), C-FM (Caucasian female).
* means statistic difference with Chinese male.
† means statistic difference with Chinese female.
‡ means statistic difference with Caucasian male.
α means statistical significance in correlation ($P<0.05$).
β means statistical significance in correlation ($P<0.01$).

Table IV. — Comparison of the morphological data with those reported in literature

Asian					Caucasian				
Authors	fML(mm)	fAP(mm)	tML(mm)	tAP(mm)	Authors	fML(mm)	fAP(mm)	tML(mm)	tAP(mm)
Cheng *et al*, 2009 (Chinese)	74.4±2.9(M) 66.8±3.11(F)	66.6±2.4(M) 61.0±24.6(F)	76.4±2.8(M) 68.8±4.6(F)	51.3±2.0(M) 45.7±1.9(F)	Lonner *et al*, 2008 (American)	76.9(M) 67.49(F)	62.27(M) 56.32(F)		
Kwak *et al*, 2007 (Korea)			76.1±4.0(M) 67.6±3.1 (F)	48.2±3.3(M) 43.3±2.3 (F)	Mensch and Amstutz, 1975 (American)	82.1±4.7(M) 76.8±2.6(F)		80.3±3.7(M) 70.1±2.8(F)	54.3±3.6(M) 46.0±2.1(F)
Ha and Ha, 2012 (Korea)	74.8(M) 68.2(F)	66.3(M) 60.8(F)	74.2(M) 67.6(F)	52.6(M) 47.4(F)	Chin *et al*, 2002	71.6(C)	57.3(C)		
Uehara *et al*, 2002 (Japan)			77.49(M) 69.5(F)	54.1(M) 49.2(F)					
Kwak *et al*, 2010 (Korea)	74.4(M) 65.9(F)	46.2(M) 41.2(F)							
Lim *et al*, 2012 Korea (MRI)	81.5±5.7(M) 76.7±3.7(F)	59.0±4.1(M) 58.4±3.1(F)	80.6±6.3(M) 70.0±3.5(F)	52.7±5.02(M) 45.7±3.3(F)					
Our study (Chinese)	72.7±3.8(M) 64.4±2.6(F)	56.5±2.5(M) 52.8±2.6(F)	77.2±3.3(M) 69.1±2.8(F)	49.6±2.4(M) 44.2±2.3(F)	Our study (American)	74.6±3.9(M) 65.4± 1.4(F)	59.6±3.2(M) 55.4±2.8(F)	79.4±4.3(M) 70.2±2.7(F)	49.5±2.9(M) 45.2±2.3(F)

M : male, FM : female, C : combined

reported larger tAP by directly measuring the CT images of the knee. Mensch *et al* (*22*) reported similar data on tAP and tML compared to our measurements of Caucasian subjects. Similarly to the studies of *et al* (*19*) and Hitt's (*14*), all subjects of our study showed a decreasing aspect ratio (tML/tAP) as the tAP dimension increased.

Smaller dimensions of the female knees than those of the males were also reported by Yue *et al* (*29*). The size differences may be related to the body height differences among the subject groups (Table I) (*25*). Our data indicated that both Chinese and Caucasian females have narrower femoral condyles than the males if their fAPs are the same, similar to the report of Lonner *et al* (*21*) and Hitt *et al* (*14*). This may explain the observation that females tend to have more mediolateral overhangs than males using contemporary TKA components (*7,14,15*). Although "undersizing the femur implant" in female patients may be beneficial in reducing the medial-lateral overhang, it could alter the anteroposterior coverage too, thus affecting the flexion gap and soft tissue balancing (*11*) as well as lowering the patellofemoral stresses (*14*). Another interesting point is that under a given fAP, the Chinese males have a larger fML than the Caucasian males, implying that if the femoral implant size was selected according to the fAP, Chinese males may tend to be mediolaterally under-covered using contemporary TKA components.

Under a given tAP, the data indicated that the Chinese and Caucasian females have narrower tibial platform than males, and the Chinese males have narrower tibial platform than the Caucasian males. The narrower platform implied a potential mediolateral overhang or an anteroposterior under-coverage if downsizing the component. These may have implications in soft tissue balancing and post-operative tibia positioning (*27*). Therefore, the tibia component may need to consider sex variations as well as racial-geometric features.

The relationship between the femur and tibia is seldom discussed in literature. Chen *et al* (*5*) examined the relation between fAP and tML and showed similar trend to our results. Our data indicated that the tAP/fAP and tML/ fAP "ratios" change their values with sex, race and knee size. With a given fAP, males have a larger tibia platform than that of females, and the Chinese males have a larger tibia platform than Caucasian males. These racial and sex differences may explain the femorotibial morphology mismatch (*23,28*) of currently used prostheses when used in different sexes and races. In TKA surgeries of Chinese patients, it often needs to choose a tibial component that is larger or smaller than the one that matches the femoral component, especially in fixed bearing systems. However, undersizing the tibia component to avoid ML overhang may lead to more tibia AP under-coverage and result in implant subsidence (*2*).

Our data indicated that we could use the fAP as a guide to predict other three parameters (fML, tAP and tML). The femur and tibia could be considered as a whole in designing implant size matching. Therefore, the fAP could be used as a pre-operative planning parameter to simply the planning procedure.

One limitation of our study is that the morphologic measurements of the Caucasian population were done on the MRI knee models, while the Chinese knees were measured using their CT models. Although two different imaging techniques were used, the differences resulted from the two imaging techniques should be small (*24*). Future studies should compare these anatomic knee data with the TKA dimensions used in surgeries.

CONCLUSION

This study measured the sex-specific, race-specific morphologic dimensions of both Chinese and Caucasian knees on their resected surfaces prepared to simulate TKA cuts. Racial and sex differences in knee geometries were found between the Chinese population and the Caucasian population. The relationships between the femur and tibia also showed racial and sex differences. These results may provide guidelines for future development of sex-specific as well as race-specific total knee replacement prostheses.

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