

Three-Dimensional Morphometry of Normal Japanese Knees For Designing Total Knee Arthroplasty

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Abstract

Background: To examine racial and sex-related differences in bone morphology and to determine whether it is necessary to take sex-related and ethnic differences into account in designing artificial knee joints.

Methods: Hundred Japanese women normal knees, 88 Japanese men normal knees, and 18 Caucasian women normal knees were examined. Knee joints were measured to enable selection and design of artificial knee joints based on assumed bone resection face dimensions in TKA.

Results: The dimensional measurements were performed by reading the three-dimensional CT based bone model. F-MAP/F-ML and F-LAP/F-ML relative to F-ML dimensions and T-MAP/T-ML and T-LAP/T-ML relative to T-ML dimensions were determined in both sexes.

Results: In both sexes and in both the femur and tibia, the value increased with decreasing size. Therefore, the width narrowed with decreasing size. It was considered that the width may be narrower in women than in men because women have smaller bone sizes than men. The matching ratio was considered to improve as the aspect ratio is adjusted according to the size when an artificial joint is designed. There were no significant differences in the measured sagittal flexion angle between the Japanese and Caucasian women.

Conclusion: The individual differences were greater than the racial differences; therefore, we consider that there is no significant need to change the shape of the artificial knee joint according to racial differences in bone morphology.

Introduction

Total knee arthroplasty (TKA) is recognized as one of the most successful orthopedic surgical procedure in the 20th century for the treatment of knee arthrosis in terms of pain mitigation and improvements in quality of life and joint function [1, 2]. However, further improvements in postoperative knee joint function are needed, including pain mitigation, adequate postoperative range of motion, and elimination of abnormal feelings during joint motion [3, 4]. Such functional improvements seem to necessitate the provision of artificial knee joints of appropriate shapes and sizes suited to individual patients' culture, lifestyle, and bone morphology, all of which exhibit sex-related, ethnic, and even individual patient-related differences. For example, one study showed that in TKA, a ≥ 3 -mm overhang of a femoral component approximately doubled the likelihood of clinically important knee pain 2 years postoperatively [5]. In addition, component underhangs pose a risk of sagging of the bone that supports the artificial joint as cancellous bone and are considered to pose a risk of postoperative hemorrhage due to exposure of cancellous bone.

Several studies have been conducted to design artificial knee joints of different shapes and sizes and to clarify the anatomical and morphological differences in bone between the two sexes and among ethnic groups (races) [6–22]. With regard to sex-related differences, some studies have shown that the femur is

longitudinal with a narrower medial-lateral (ML) length relative to anterior-posterior (AP) length in women than in men [13], that the femoral anterior patellar groove is shallower in women than in men [15], that the joint line varus is smaller in women than in men, and that the Q-angle of the patellar groove is larger in women than in men [8, 16]. With respect to ethnic (racial) differences, Kim et al. [23] reviewed 30 studies that utilized equivalent measuring methods to summarize the bone morphological differences among Southeast Asians (i.e., patients from China, Japan, Korea, Malaysia, and Thailand), Caucasians, Blacks, and Indians. The authors found that the femur tended to be laterally long with a shorter AP length in Southeast Asians than in Caucasians and that the tibia tended to longitudinally long with a longer AP length in Blacks than in Caucasians.

Measurements have historically been taken from donated bones or directly from bones during TKA surgery. In recent years, it has been possible to obtain accurate measurements from bone models prepared using computed tomography (CT) and magnetic resonance imaging data.

In the present study, knee joints of Japanese people were measured to enable selection and design of artificial knee joints based on assumed bone resection face dimensions in TKA. Femurs of Caucasians were also measured using the same procedures. The results were compared to examine racial and sex-related differences in bone morphology and to determine whether it is necessary to take sex-related and ethnic differences into account in designing artificial knee joints.

Materials And Methods

The study population comprised Japanese adults (mean age, 51.7 ± 23.4 years) who were enrolled in the study after approval of the ethics committee of a collaborating research institute. CT data on normal anonymized knees considered by orthopedic surgeons to have no distinct deformations were obtained from the participating Japanese institutions. Without taking laterality into consideration, 100 knees were randomly selected from 100 women, and 88 knees were randomly selected from 88 men. CT data on fresh frozen bone specimens for surgical training were also obtained from 18 knees from 18 United States Caucasian women (mean age, 67.2 ± 9.8 years). For the surgical training, these Caucasian women had been selected to have relatively small builds like those of Japanese women.

CT data with a slice thickness of 1.0 to 1.5 mm were processed by a CT value binarization method using Mimics medical image processing software (Materialise N.V., Leuven, Belgium) to develop a three-dimensional bone model with a threshold of 200 [24, 25].

The measuring coordinates were designed and the dimensional measurements were performed by reading the three-dimensional bone model using three-dimensional computer-aided design software (Materialise 3-matic, Ver. 8; Materialise N.V.). The femoral mechanical axis (line between the center of the femoral head and center of the knee = point at which the separated medial and lateral condyles first come into contact with each other distally) served tentatively as the Z-axis in an orthogonal coordinate system. The surgical epicondylar axis (line between the center of the medial collateral ligament enthesis and the center of the lateral collateral ligament enthesis) was projected on a plane at a right angle with

respect to the Z-axis to make it parallel to the X-axis [26, 27]. With the normal line of the ZX plane as the Y-axis, the femur was tilted so that the projection line of the femoral distal anatomical axis (line passing the point closest to the center of the cortical bone in the range of two-fifths of the distal femur) was aligned with the Z-axis on the YZ plane (= sagittal plane). Thus, the plane perpendicular to the functional axis on the coronal plane and to the surgical epicondylar axis on the sagittal plane formed the XY plane, and this was consistent with bone resection perpendicular to the intramedullary rods with an adjusted valgus angle. The tibial mechanical axis (line passing the point closest to the center of the cortical bone in the range from the tibiofibular head to the distal tibiofibular joint notch) was aligned to the Z-axis in an orthogonal coordinate system [28], and an Insall line perpendicular to the Z-axis (line between the posterior cruciate ligament enthesis and a position one-third from the medial tibial tuberosity) was projected parallel to the Y-axis [29].

Figure 1A and B show the measuring positions in the femur and tibia, respectively. For the femur, the angle between the mechanical axis and femoral distal anatomical axis in the sagittal plane (i.e., sagittal flexion angle) was measured. The angle between the surgical epicondylar axis and the posterior condyle line (i.e., posterior condyle angle), was measured. The distal bone was resected 1 mm proximal to the femoral intercondylar space (parallel to the XY plane), and the anterior bone was resected at the anterior reference position (parallel to the ZX plane; the height was proximal by a length one-tenth of the femur length from the distal resection face). The following parameters were measured after distal and anterior resections: the femoral medial AP length (F-MAP), femoral lateral AP length (F-LAP), and transverse length of the femur at the surgical epicondylar axis (SEA) position on the resection face (F-ML). The thicknesses of resected bone pieces were measured as the distal medial (MD), distal lateral (LD), anterior flange medial (MF), and anterior flange lateral (LF) thicknesses.

The proximal tibia was resected 10 mm distal to the tibial lateral joint face (at a position approximately one-half of the AP length and one-fifth of the ML length) without posterior tilt. The tibial medial AP length (T-MAP) at a position one-fourth medial of the ML length, the tibial lateral AP length (T-LAP) at a position one-fourth lateral of the ML length, and the tibial maximum transverse length (T-ML) on the resection face were measured.

The measurements were averaged to obtain the mean values of various parameters, and standard deviations were calculated. As size reference values for designing TKA, aspect ratios were determined by dividing the measured values by F(T)-ML. In addition, to check for changes in the aspect ratio size, the relationship between the aspect ratio and F(T)-ML dimensions was determined for each sex to calculate the correlation coefficient R of the regression line. Data were tested for significant differences between the two sexes using Wilcoxon's rank sum test (Mann–Whitney U test), a nonparametric test, with a *P* value of $\leq .05$ considered to indicate a significant difference.

Results

The measurements obtained from the Japanese subjects are shown in Table 1. Figure 2 shows graphic representations of F-MAP and F-LAP versus F-ML and T-MAP and T-LAP versus T-ML. For the femur, the sagittal flexion angle used to adjust the sagittal plane was significantly lower in men than in women (2.1 ± 1.9 vs. 2.7 ± 1.1 degrees, respectively). The posterior condyle angle used to adjust the femoral circumflex alignment was not significantly different between the two sexes (2.5 ± 2.2 degrees in women and 2.7 ± 1.5 degrees in men). The MD thickness was 8.9 ± 1.4 mm in women and 9.1 ± 1.4 mm in men, and the LD thickness was 5.6 ± 1.0 mm in women and 5.6 ± 1.0 mm in men. The MF thickness was 2.3 ± 2.1 mm in women and 2.7 ± 1.8 mm in men, and the LF thickness was 6.6 ± 1.9 mm in women and 7.6 ± 1.9 mm in men. After distal and anterior resection of the femur, F-ML was 66.8 ± 3.6 mm in women and 74.3 ± 3.0 mm in men, F-MAP was 56.9 ± 3.7 mm in women and 62.6 ± 3.4 mm in men, and F-LAP was 55.1 ± 3.1 mm in women and 60.3 ± 3.2 mm in men; all parameters were significantly greater in men. Following proximal resection of the tibia, T-ML was 70.8 ± 3.7 mm in women and 78.0 ± 3.1 mm in men, T-MAP was 53.6 ± 2.8 mm in women and 58.4 ± 2.9 mm in men, and T-LAP was 45.3 ± 2.5 mm in women and 50.1 ± 2.7 mm in men; all of these parameters were greater in men. The mean difference between F-ML and T-ML was 3.9 ± 2.0 mm; the tibia had the larger value.

Table 1
List of measurements from Japanese subjects by sex

	Female (N = 100)		Male (N = 88)		PValue
	Average	SD	Average	SD	
SFA (degrees)	2.7	1.1	2.1	1.9	.0014 *
PCA (degrees)	2.5	2.2	2.7	1.5	.2947
MD (mm)	8.9	1.4	9.1	1.4	.4706
LD (mm)	5.6	1.0	5.6	1.0	.8612
MF (mm)	2.3	2.1	2.7	1.8	.2518
LF (mm)	6.6	1.9	7.6	1.9	.0005 *
F-ML (mm)	66.8	3.6	74.3	3.0	<.0001 *
F-MAP (mm)	56.9	3.7	62.6	3.4	<.0001 *
F-LAP (mm)	55.1	3.1	60.3	3.2	<.0001 *
T-ML (mm)	70.8	3.7	78.0	3.1	<.0001 *
T-MAP (mm)	53.6	2.8	58.4	2.9	<.0001 *
T-LAP (mm)	45.3	2.5	50.1	2.7	<.0001 *

SD, standard deviation; SFA, sagittal flexion angle; PCA, posterior condyle angle; MD, distal medial; LD, distal lateral; MF, anterior flange medial; LF, anterior flange lateral; F-ML, femoral maximum transverse length; F-MAP, femoral medial anterior-posterior length; F-LAP, femoral lateral anterior-posterior length; T-ML, tibial maximum transverse length; T-MAP, tibial medial anterior-posterior length; T-LAP, tibial lateral anterior-posterior length; *, significant difference.

When the measured values were divided by F(T)-ML to obtain the aspect ratios, which were then compared between the two sexes, F-MAP/F-ML and F-LAP/F-ML were higher in women than men, with a significant difference in F-LAP/F-ML. MD/F-ML and LD/F-ML were significantly higher in women than men. There were no significant sex-related differences in MF/F-ML or LF/F-ML. There were also no significant sex-related differences in T-MAP/T-ML or T-LAP/T-ML (Table 2).

Table 2
Quotients of measurements from Japanese men and women divided by ML

	Female (N = 100)		Male (N = 88)		PValue
	Average	SD	Average	SD	
F-MAP/F-ML	0.853	0.052	0.843	0.040	.1070
F-LAP/F-ML	0.825	0.045	0.812	0.041	.0082 ✽
MD/F-ML	0.134	0.021	0.123	0.018	.0002 ✽
LD/F-ML	0.084	0.015	0.075	0.013	<.0001 ✽
MF/F-ML	0.035	0.031	0.036	0.025	.7421
LF/F-ML	0.099	0.027	0.102	0.025	.3023
T-MAP/T-ML	0.757	0.031	0.752	0.025	.0939
T-LAP/T-ML	0.641	0.027	0.642	0.027	.8397

ML, medial-lateral; SD, standard deviation; F-MAP, femoral medial anterior-posterior length; F-ML, femoral maximum transverse length; F-LAP, femoral lateral anterior-posterior length; MD, distal medial; LD, distal lateral; MF, anterior flange medial; LF, anterior flange lateral; T-MAP, tibial medial anterior-posterior length; T-ML, tibial maximum transverse length; T-LAP, tibial lateral anterior-posterior length;
✽, significant difference.

Figure 3 is a graphic representation of F-MAP/F-ML, F-LAP/F-ML, T-MAP/T-ML, and T-LAP/T-ML to F(T)-ML in Japanese subjects. With regard to changes in the aspect ratio size for the femur, both F-MAP/F-ML and F-LAP/F-ML tended to decrease with increasing size; a negative correlation with a correlation coefficient R of 0.27 to 0.43 was found for the femur. There was almost no correlation between size and MD/F-ML, LD/F-ML, MF/F-ML, or LF/F-ML; the correlation coefficient R was <0.10. For the tibia, both T-MAP/T-ML and T-LAP/T-ML tended to decrease with

increasing size; a negative correlation was found (correlation coefficient R = 0.12–0.39). Table 3 compares the measurements from Japanese versus Caucasian women. Although the United States Caucasian women were selected to have a relatively small build, they had larger F-ML sizes than the Japanese women. There were no significant differences in F-MAP/F-ML, F-LAP/F-ML, MD/F-ML, MF/F-ML, and LF/F-ML; LD/F-ML alone was significantly lower in Japanese women.

Table 3
Comparison of measurements from Japanese versus Caucasian women

	Japanese (N = 100)		Caucasian (N = 18)		P Value
	Average	SD	Average	SD	
SFA (degrees)	2.7	1.1	3.0	1.1	.2963
PCA (degrees)	2.5	2.2	1.7	1.8	.3379
F-ML (mm)	66.8	3.6	67.9	2.1	.0448 *
F-MAP (mm)	56.9	3.7	58.3	2.8	.0831
F-LAP (mm)	55.1	3.1	56.9	3.2	.0138 *
F-MAP/F-ML	0.853	0.052	0.859	0.036	.6160
F-LAP/F-ML	0.825	0.045	0.838	0.043	.3494
MD/F-ML	0.134	0.021	0.138	0.019	.6003
LD/F-ML	0.084	0.015	0.094	0.017	.0124 *
MF/F-ML	0.035	0.031	0.036	0.019	.6479
LF/F-ML	0.099	0.027	0.091	0.021	.4451

SD, standard deviation; SFA, sagittal flexion angle; PCA, posterior condyle angle; F-ML, femoral maximum transverse length; F-MAP, femoral medial anterior-posterior length; F-LAP, femoral lateral anterior-posterior length; MD, distal medial; LD, distal lateral; MF, anterior flange medial; LF, anterior flange lateral; **, significant difference.

Discussion

Bone morphometry has been performed in prior studies. We attempted to comprehensively interpret the measurements from such studies to obtain basic data for designing TKA, but we encountered difficulty because of obscurities and variations in measuring methods. Comparisons of parameters obtained using different methods may produce apparent racial differences.

In the present study, bone resection face shapes likely to occur in TKA were measured to enable design of artificial knee joints. To this end, we used the measuring criteria considered to be most commonly used in TKA. For the resection planes, we assumed a coronal plane at a right angle with regard to the functional axis and a sagittal plane at a right angle with regard to the distal axis for the femur and without posterior tilt for the tibia. For circumflex alignment, the SEA served as the reference for the femur, and the Insall line served as the reference for the tibia. Because artificial knee joints involve component circumflex assumed at the time of design, the rotational relationship is reproduced at the time of reduction of the femoral and tibial components to maximize the functioning of the artificial knee joint. In this survey, measurements were taken with alignment of each of the femur and tibia models on CT images taken in a non-loaded

supine position; therefore, the angle between the femoral SEA and tibial Insall line remained unknown. Wernecke et al. [30] reported that the Insall line in extension exhibits an external rotation by a mean of 2.7 degrees with respect to the SEA and that individual differences exist. When designing an artificial joint, it seems necessary to make a dimensional correction for this angle and to have a design accommodating circumflex mismatches between the femur and tibia.

With regard to sex-related differences in measurements, Lonner et al. [13] reported that the femoral MAP/ML was narrower in women than in men (0.84 vs. 0.81, respectively). Two types of prior study involving the AP/ML ratio were identified: one with AP as the denominator and the other with ML as the denominator. Because AP dimensions occur on both the medial and lateral sides and are susceptible to circumflex alignment, we considered that ML was more useful as a size reference than AP, and ratios were calculated with ML as the denominator. In the present study, there were no significant sex-related differences in F-MAP/F-ML; however, F-LAP/F-ML was significantly narrower in women than in men, and the tendency was thus the same. For the tibia, there were no significant sex-related differences in T-MAP/T-ML or T-LAP/T-ML.

If we assume an artificial knee joint fabricated with an F-MAP of 60.0 and an F-ML of 70.7, which correspond to a femoral F-MAP/F-ML of 0.849 determined as the mean of both sexes in the present study, and given an overhang/underhang of 3 mm on one side (6 mm on both sides), for example, F-MAP/F-ML in the range of 0.78 to 0.93 will be covered. However, some knees had F-MAP/F-ML measurements outside the range of 0.78 to 0.93 (21 in 188 knees = 11%), suggesting that the proportional use of a single size can cause mismatches even in normal joints. To ensure full coverage for the bone, it seemed necessary to make at least two variations with different ratios or to provide custom-made artificial knee joints. In addition, because the medial and lateral condyles are asymmetrical, artificial knee joints with different thicknesses are more physiological. However, individual differences exist even in normal knees, and nothing more than average joint shape can therefore be attained with proportional design.

With regard to the relationship between the AP-ML aspect ratio and size, Hitt et al. [10] and Kwak et al. [17] demonstrated a correlation between AP size and ML/AP, showing that the width narrowed with decreasing size in both the femur and tibia. In the present study, to confirm size-related differences, F-MAP/F-ML and F-LAP/F-ML relative to F-ML dimensions and T-MAP/T-ML and T-LAP/T-ML relative to T-ML dimensions were determined in both sexes. In both sexes and in both the femur and tibia, the value increased with decreasing size and vice versa; therefore, the width narrowed with decreasing size, which is similar to the trends reported by Hitt et al. [10] and Kwak et al. [17]. It was considered that the width may be narrower in women than in men because women have smaller bone sizes than men. The matching ratio was considered to improve as the aspect ratio is adjusted according to the size when an artificial joint is designed.

There were no significant differences in the measured sagittal flexion angle between the Japanese and Caucasian women. A prior study showed that the Japanese femur was more anteriorly bowed [31].

Despite this greater bowing in the Japanese population, we found no significant differences in the present study; therefore, racial differences need not be taken into account when surgery is performed using bowing-free intramedullary rods approximately 150 mm in length. Nor was there any significant difference in F-MAP/F-ML and F-LAP/F-ML, unlike the results reported by Kim et al. [23]. In the present study, the individual differences were greater than the racial differences; therefore, we consider that there is no significant need to change the shape of the artificial knee joint according to racial differences in bone morphology.

Conclusions

The individual differences were greater than the racial differences; therefore, we consider that there is no significant need to change the shape of the artificial knee joint according to racial differences in bone morphology.

Abbreviations

TKA, total knee arthroplasty; ML, medial-lateral; AP, anterior-posterior; CT, computed tomography; SEA, surgical epicondylar axis; MD, distal medial; LD, distal lateral; MF, anterior flange medial; LF, anterior flange lateral; F-ML, femoral maximum transverse length; F-MAP, femoral medial anterior-posterior length; F-LAP, femoral lateral anterior-posterior length; T-ML, tibial maximum transverse length; T-MAP, tibial medial anterior-posterior length; T-LAP, tibial lateral anterior-posterior length

Declarations

Ethics approval and consent to participate

This study was approved by the Institutional Review Board and Ethics Committee of Osaka University Hospital (IRB approval number: 10189-6). and informed consent was obtained from all participants.

Consent for publication

The authors affirm that the human research participants provided informed consent for publication.

Availability of data and materials

The datasets generated and/or analyzed during the current study are not publicly available because other studies are being carried out based on these data, but are available from the corresponding author upon reasonable request.

Competing interests

The authors declare that they have no competing interests.

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Authors' Contributions

TT designed the study and did investigation, conceptualization, methodology, and the writing the original draft of the manuscript. MS, TN and KR contributed investigation and analysis. HT supervised this project along with reviewed and edited the manuscript. All authors read and approved the final manuscript.

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Figures

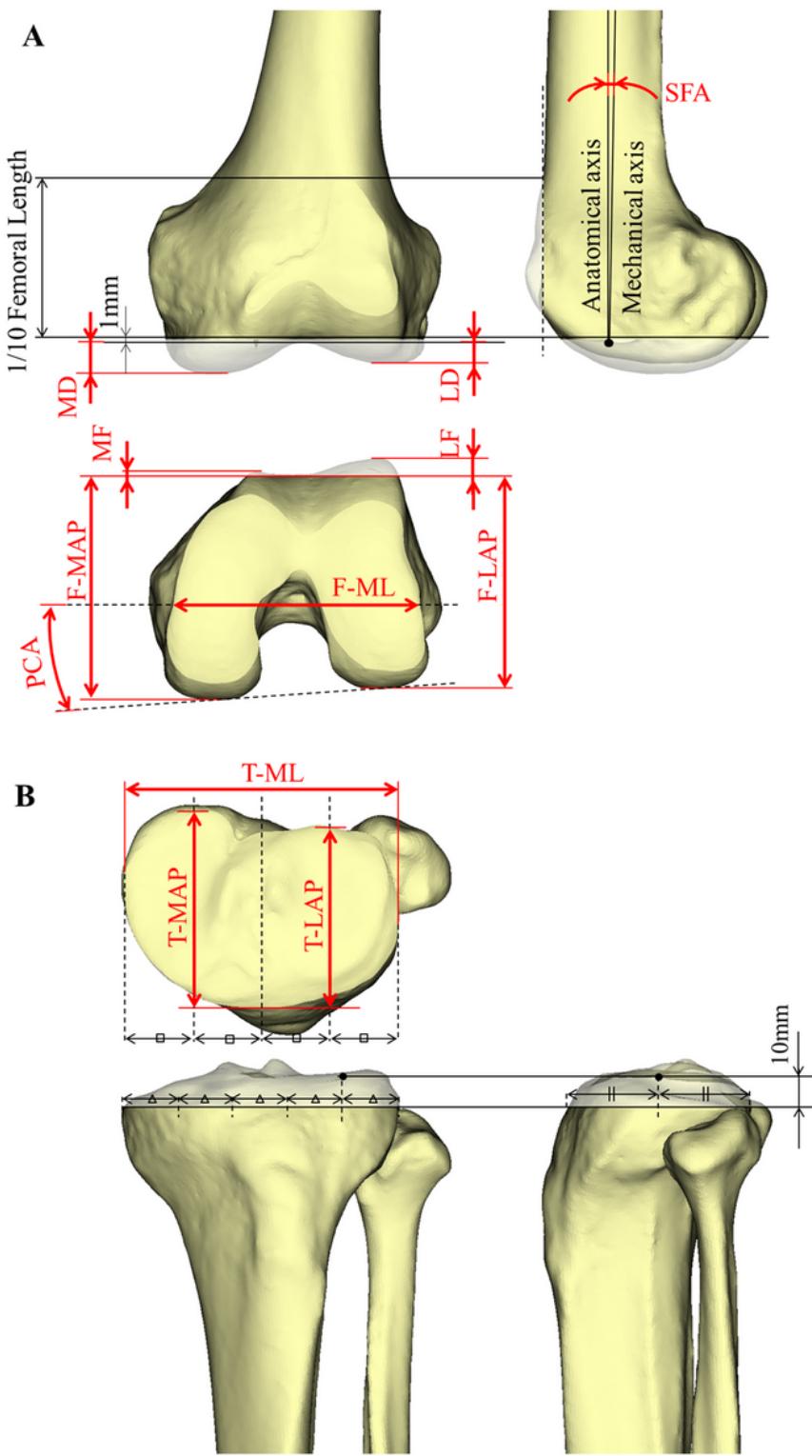


Figure 1

Anatomical sites for measurements from Japanese subjects. (A) Femoral sites. SFA indicates the angle between the functional femoral axis and distal femoral axis. PCA indicates the angle between the SEA and PC line. MD and LD represent the distances from the intercondylar space to the medial and lateral joint face, respectively. MF and LF represent the distances from the anterior resection face to the medial and lateral apexes of the anterior patellar groove, respectively. F-ML, F-MAP, and F-LAP represent the

transversal width at the position of the SEA projection on the resection face 1 mm proximal to the intercondylar space and the distances from the medial and lateral posterior condyles to the anterior resection face, respectively. (B) Tibia position. T-ML, T-MAP, and T-LAP represent the maximum width on the resection face 10 mm distal to the lateral joint face and the distances from the medial and lateral posterior condyles (positions one-fourth of T-ML) to the most anterior position on the contour, respectively. SFA, sagittal flexion angle; PCA, posterior condyle angle; SEA, surgical epicondylar axis; MD, distal medial; LD, distal lateral; MF, anterior flange medial; LF, anterior flange lateral; F-ML, femoral maximum transverse length; F-MAP, femoral medial anterior-posterior length; F-LAP, femoral lateral anterior-posterior length; T-ML, tibial maximum transverse length; T-MAP, tibial medial anterior-posterior length; T-LAP, tibial lateral anterior-posterior length;

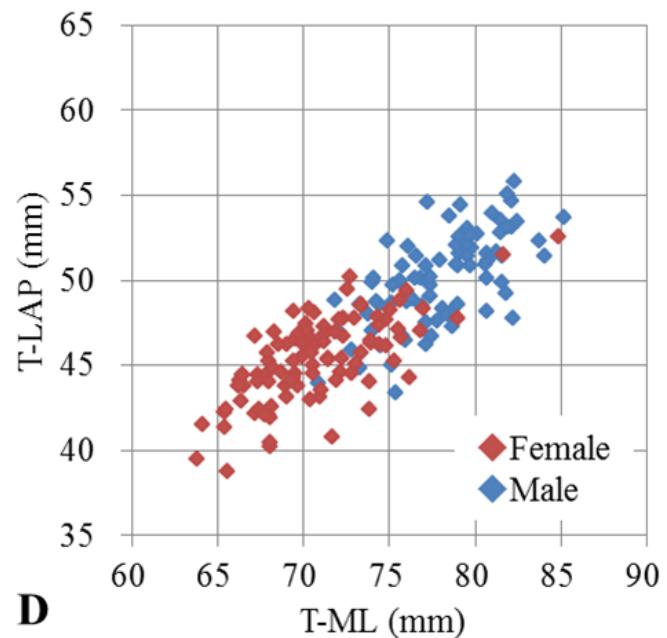
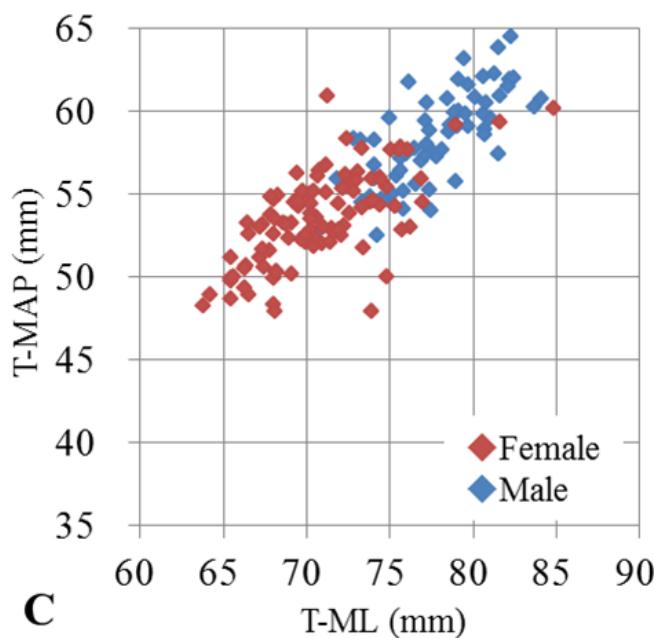
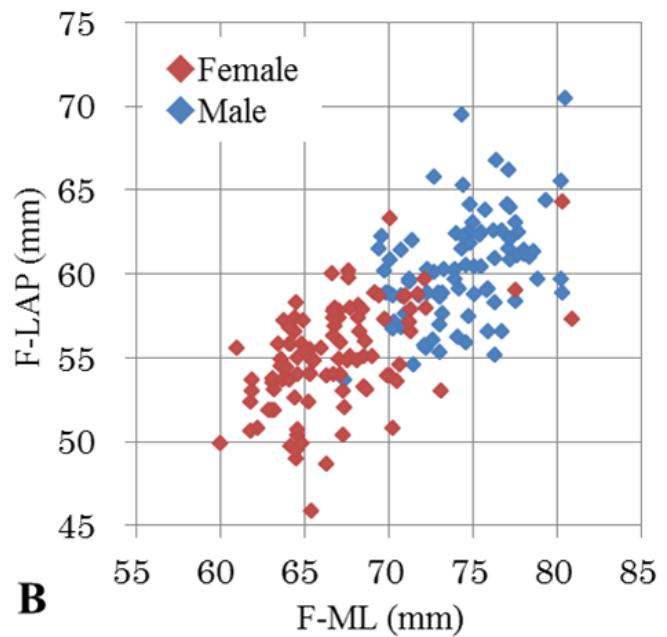
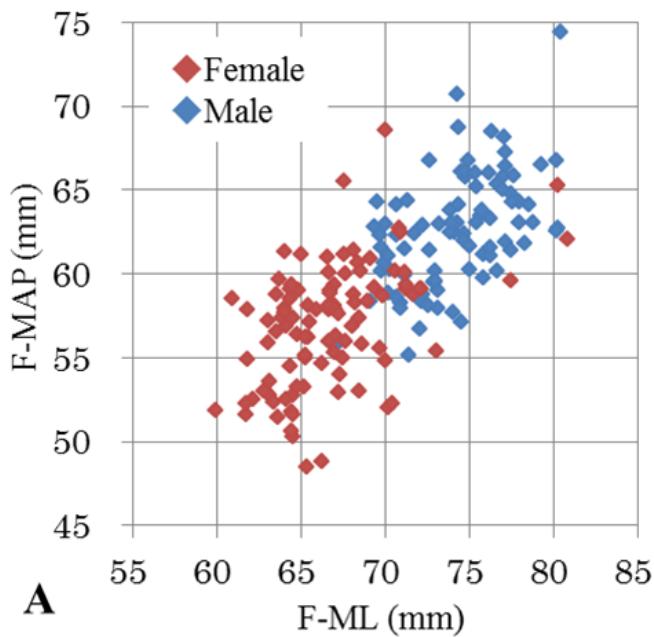
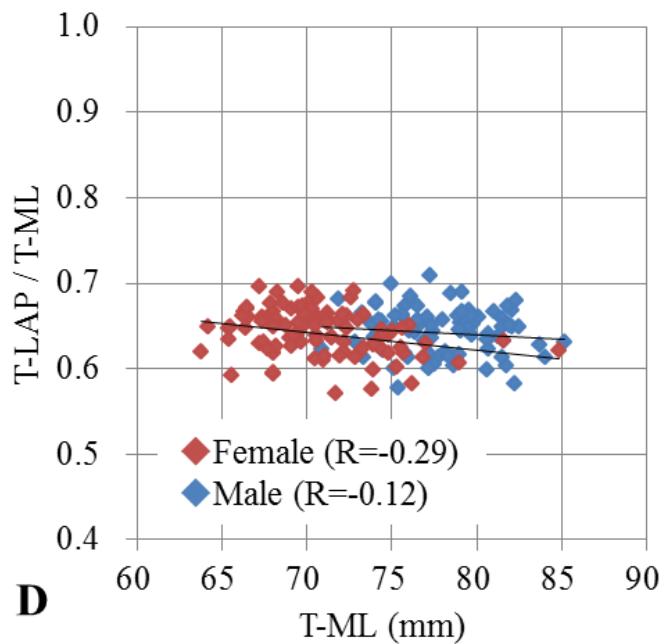
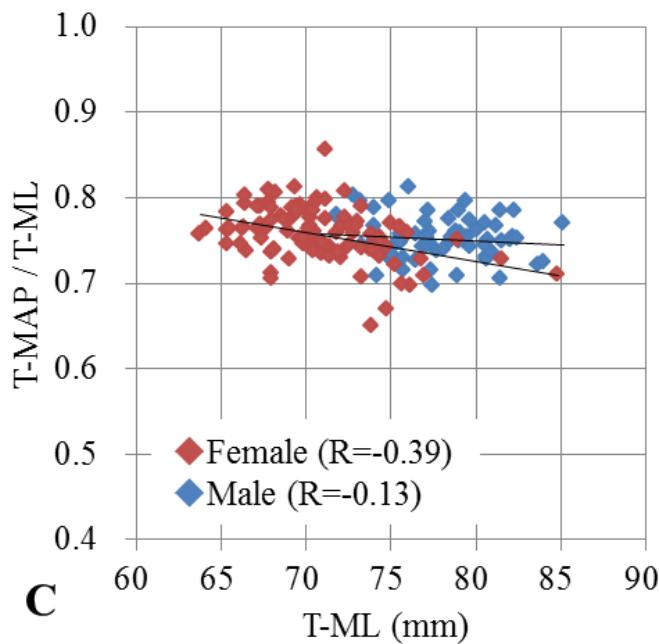
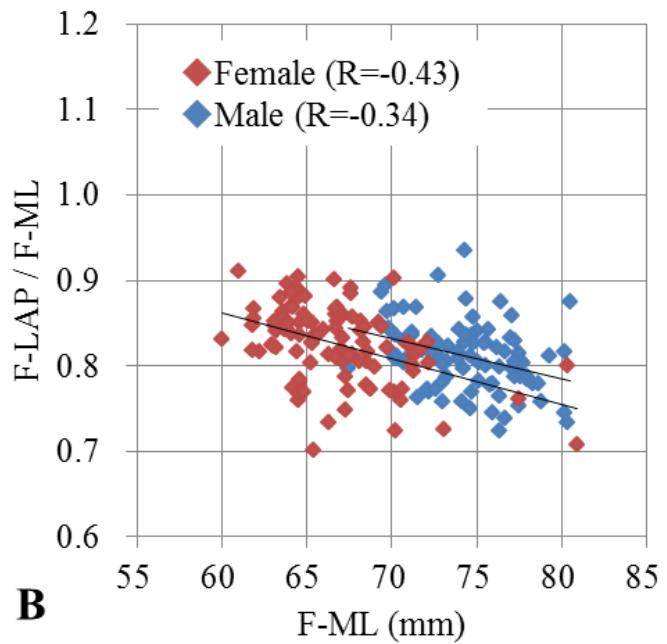
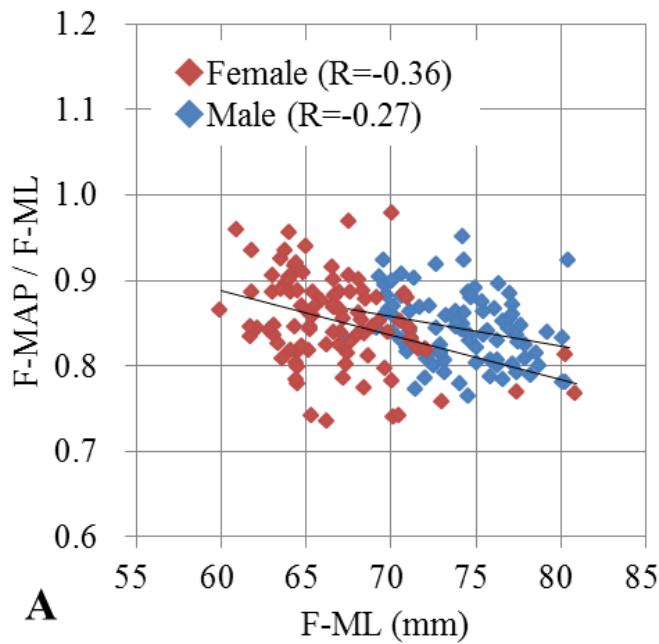


Figure 2

Relationship between ML and AP parameters in Japanese subjects. (A) Relationship of F-MAP to F-ML. (B) Relationship of F-LAP to F-ML. (C) Relationship of T-MAP to T-ML. (D) Relationship of T-LAP to T-ML.
ML, medial-lateral; AP, anterior-posterior; F-MAP, femoral medial anterior-posterior length; F-ML, femoral maximum transverse length; F-LAP, femoral lateral anterior-posterior length; T-MAP, tibial medial anterior-posterior length; T-ML, tibial maximum transverse length; T-LAP, tibial lateral anterior-posterior length

**Figure 3**

Size dependency of AP/ML ratios in Japanese subjects. (A) Relationship of F-MAP/F-ML to F-ML. (B) Relationship of F-LAP/F-ML to F-ML. (C) Relationship of T-MAP/T-ML to T-ML. (D) Relationship of T-LAP/T-ML to T-ML. AP, anterior-posterior; ML, medial-lateral; F-MAP, femoral medial anterior-posterior length; F-ML, femoral maximum transverse length; F-LAP, femoral lateral anterior-posterior length; T-MAP, tibial medial anterior-posterior length; T-ML, tibial maximum transverse length; T-LAP, tibial lateral anterior-posterior length