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Morphometric Analysis of the Knee: A Comprehensive Evaluation of Knee Morphology in Designing Arthroplasties of Knee

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Salient Features

- A conceptual knowledge of knee architecture is important in designing various implants in patients with severe osteoarthritis and other bone deformities.
- Two types of methodologies have been followed for knee morphology assessments: (1) clinical intraoperative measurements and (2) computational analysis directly on medical images of knee.
- The metrics used for width are the mediolateral (ML) width of the proximal tibia, distal femur, and patellar, whereas for length determination is the anterolateral (AP) length of the proximal tibia and distal femur, and the proximal distal (PD) length of the patella.
- The angle between inclination of the tibial plateau and the long axis of the tibia shaft and the posterior slope of the tibial component influences various aspects of the knee kinematics and therefore plays an important role in implant fixation and wear of polyethylene insert.
- The commonly accepted threshold for implant overhang is 3 mm. Excessive overhang causes pain and worsens outcomes of knee arthroplasties. However, they can be tackled intraoperatively by reducing the size of implant.
- Novel metrics considered in tibial architecture are areas for the entire resection surface and each of the medial and lateral plateaus, areas of the bounding boxes for the entire resection and each of the medial and lateral plateaus, and radii of the tibial anterior periphery on the medial and lateral plateaus.
- Patellar stock thickness should be at least 12 mm, and bone stock should be maintained after resection to provide sufficient biomechanical strength of the composite.
- Computational methods such as shape models provide an analytic tool for the study of anatomy such as individual bone types in the knee or even the entire knee joint complex.
- The intrinsic differences in knee morphology across ethnics and genders that may in part explain the variable clinical outcomes.
- The disease progression or deformity in the knee may lead to alternation of its bony structure. Therefore, clinicians commonly believe that resections with a deviation within ±3° in alignment are acceptable, while the account of bone resected may be less under control depending on the reference point for resection depth, device thickness to match, and sometimes the quality of the bone.
- The anatomical designs exhibited improved latero-posterior (LP) coverage than the symmetrical standard designs in the ML and MP dimensions.

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22.1 Introduction

The primary objective of knee arthroplasty is to alleviate chronic pain and reinstate functionality of the impaired knee [1, 2]. Over the history of its application, the design of the prothesis has been improved tremendously in order to satisfy elevated demand and expectation from the patients. The modern knee prothesis are no longer designed for only providing preservation of the knee joint, pain relief, and (maybe) partial restoration of some functionalities for daily living. Nowadays, the implants are refined into optimal features in the design size and shape, advanced materials, surgical instruments and approach, and advanced postoperative recovering management and rehabilitation regime [3]. For example, in TKA surgery, the current implants are expected to have more than 90% 10-year survivorship with many implantations survived much longer.

It has been reported by meta-analysis that 82% of the total knee replacements lasted over 25 years after the surgery [4]. The leading etiologies for TKA failures have been identified as microbial infections, instability, malfunctioning of the prosthetic, aseptic loosening, implant fracture, gangrene in the patella, and improper axial positioning [5, 6]. However, even with a well-implanted knee confirmed by clinical evidences such as radiographs and in-office functional tests, there is still a group of approximately 20% of the TKA patients who still complain about the outcomes of the surgery [7].

One important contributing factor for implant loosening and satisfaction may be the anatomic fit of the implants. Excessive implant overhang over the bony resection boundary, especially in the mediolateral direction, has been shown to associate with soft tissue impingement and inflammation and cause significantly worse knee outcomes and pain [8–10]. A commonly accepted threshold for implant overhang is 3 mm as demonstrated in several studies to cause significant impact in the knee biomechanical and clinical outcomes [8–10]. Intraoperatively, a surgeon can avoid excessive overhang by reducing the size of the implant. However, the downsizing of the implant may lead to another issue, which is the reduced bony coverage by the implant. This inevitably results in the implant sits on the "softer" (cancellous) area of the resection surface and therefore may compromise the fixation and optimal load transfer between the implant and the bone with the reduced cortical support.

With the TKA implantation on the tibia, internally rotating the tibial implant may avoid the downsizing of the implant, but the internal rotation can be detrimental to the proper rotational alignment of the implantation, leading to heightened risks of patellofemoral complications, pain, and implant failure [11–14]. The resolution to the struggle between minimizing implant overhang, improving implant bony coverage, and maintaining proper rotation is the anatomical appropriateness in the implant design. To this point, it is critical to study knee morphology and its variation globally for a better understanding of current knee designs and the development of the next generation that properly fits the target patient population.

22.2 Morphological Analysis in Knee Arthroplasty

Arthroplasties in the knee should ideally consider the bony anatomy of the specific patient and operative site. This requires a good understanding of the knee morphology concerning the target treatment population. Studies of the knee morphology with respect to knee arthroplasty have been mainly using two types of methodologies: (1) clinical intraoperative measurements [15, 16] and (2) computational analysis directly on medical images of the knee or the virtual surface segmented from the medial images [17–21]. Although intraoperative measurements have the strength of providing real-world information on the clinically observed morphology from the actual targeted patient population, there are many setbacks in these studies. First, surgical variability is involved in the preparation of the bony resections; especially the reported studies were based on conventional surgery without the availability of intraoperative guidance (robots or surgical navigation) to minimize the surgical error.

Second, the manual measurements on the bony surface can be impacted by human error, joint environment (soft tissue and cartilage), and the inconsistency of measurement locations across samples. Last, the number of available samples is often small and imbalanced in terms of patients' ethnicity and gender due to the difficulty of recruiting patients into a large-scale study under clinical setting.

In contrast, computational studies pose the strength regarding removing variability in the data by the inclusion of multi-ethnic bone database with the potential of constant expansion of the study size by adding more bones and consistent and precise execution of the measurement following predefined algorithms. In addition, the ability to fully control the computational morphological studies provides possibility to compare the results from multiple studies given they are performed under the same computational protocol.

Irrespective to the methodology and bone type (femur, tibia, and patella), the morphometric measurements in the knee area focused on a common set of size and shape metrics. These measurements are mainly driven by the focus of proper implant fit during arthroplasty, as insufficient bony coverage may be detrimental to the longevity of biomechanical fixation of the implant, and the presence of excessive implant overhang has been shown to associate with soft tissue impingement and inflammation and cause significantly worse knee outcomes and pain [8–10]. This set of metrics are generally used to measure the dimensions of the articulating area in the bone, namely (1) width: the mediolateral (ML) width of the proximal tibia, distal femur, and patellar; and (2) length: the anterolateral (AP) length of the proximal tibia and distal femur, and the proximal distal (PD) length of the patella. Furthermore, the ratio between medial and lateral sides of the bone in these dimensional measurements (aspect ratio) is commonly used to depict the asymmetry between the two compartments, which is a representation of the shape of the bone. These metrics have been used to quantify knee morphology based on either the native bone or specific arthroplasty resection scenarios (Table 22.1).

In a 2011 study, morphometric measurements were reported by Yue et al. [19] on the size of the native intact proximal tibia by the AP lengths on each of the medial and lateral plateaus and the ML width. Similarly, for the native intact distal femur, the overall AP and ML dimensions were measured. From the measured size metrics, aspect ratios were calculated as the ratio between the measured ML and AP dimensions for the femur and tibia, respectively. Although the studies on the native intact knee provided insights on

Table 22.1 Illustration on AP, AM measurements on the femur and tibia

	Morphometrics	
Bone	Size	Shape
Native tibia	AP dimension (overall, medial, lateral) ML dimension	Overall aspect ratio
Resected tibia (TKA as example)	AP dimension (overall, medial, lateral) ML dimension Resection area (overall, medial, lateral) Boxiness (overall, medial, lateral) Anterior radii (medial, lateral)	Aspect ratio (overall, medial, lateral) Asymmetry between medial and lateral plateaus (area, boxiness, anterior radii)
Femur	AP dimension (overall, medial, lateral) ML dimension (multiple locations)	Aspect ratio Posterior condylar offset Trochlear orientation Trochlear sulcus angle
Native patella	ML dimension PD dimension ML location of the ridge Thickness	Aspect ratio

the general joint morphology, most studies were interested in the assessment under a surgical scenario as it provided a further understanding of knee morphology specifically related to a particular arthroplasty application. Yang et al. [15] studied in tibial implants that the AP and ML dimensions were measured on the resected proximal tibia from actual TKA patients intraoperatively [15].

A 2008 study shed a light on the difference between the medial and lateral plateaus under the application of UKA [22]. The data cumulated from numerous resection-specific measurements not only provide the knowledge on the average size and shape of the bone restated to arthroplasty and their associated variability (standard deviation), but also serve as the basis for the identification of common characteristics in the bone morphology to guide development of new arthroplasty implants for the application across multiple patient populations.

One well-established, universally applicable knowledge is that based on either native or resected tibia, a positive correlation between the size metrics, such as ML and AP dimensions, bone length, and patient's height is revealed. There is also a well-accepted consensus that the medial and lateral compartments of each bone type in the knee demonstrated an asymmetry (ML/AP aspect ratio) that revealed the medial compartment to be larger. The specific correlation formula and aspect ratio calculated may be used as a meaningful indication for the design and use of associated implants for the treatment population.

In addition to the common list of dimensional measurements and aspect ratios mentioned above, other metrics were used to quantify knee morphology specifically to individual bone types and arthroplasty applications. Quantified as the angle between inclination of the tibial plateau and the long axis of the tibia shaft (multiple definitions exist by using mechanical axis, anatomical axis, or anterior cortex of the proximal tibial) [23], the posterior slope of the tibial component influences various aspects of the knee kinematics and therefore plays an important role in implant fixation and wear of polyethylene insert [24, 25]. An increased posterior slope has been shown to result in greater anterior translation of the tibia during weight-bearing activities and increased strain on the ACL with more substantial compressive loads [26–31]. Additionally, some authors have recently discussed modification of the TS through tibial deflexion osteotomy as an important surgical consideration in patients with ACL injuries with excessive TS. However, data currently remain limited to support this approach [32–36].

Novel metrics have been observed in an Indiana study [37] for the morphology of tibial resection during TKA, including: (1) areas for the entire resection surface and each of the medial and lateral plateaus; (2) areas of the bounding boxes for the entire resection and each of the medial and lateral plateaus; and (3) radii of the tibial anterior periphery on the medial and lateral plateaus. Using the newly introduced size metrics, several definitions of asymmetry were developed to descript the shape of the resection morphology as the ratio between the medial and lateral plateaus. These additional morphometric provided further understanding of tibial morphology in relation to TKA application for the evaluation and development of modern anatomic implant designs. A number of additional femur-specific metrics were also introduced, such as posterior offset of the femoral condyles; depth, width, and angle of the femoral sulcus; and orientation of the trochlear groove. This expanded list of measurements on the femur is needed as the metrics correspond to great clinical relevance to specific arthroplasty considerations. Specifically, the restoration of the original femoral posterior condylar offset (PCO), measured as the maximum thickness of the posterior condyle projecting posteriorly to the tangent of the posterior cortex of the femoral shaft, is important to maximize postoperative range of motion (ROM), avoid impingement, improve knee kinematics, and minimize flexion instability after TKA [38–41]. The measurements on the sulcus morphology, as well as the orientation of the trochlear groove, all have profound indications in both disease progression and outcomes of the patellofemoral joint [42, 43].

In the patella, the thickness of the bone stock is a critical morphometric to be considered under resurfacing surgery, as at least 12 mm bone stock should be maintained after resection to provide sufficient biomechanical strength of the composite [44] and the original thickness should be restored as close as possible after the resurfacing for the preservation of the extensor efficiency. The position of the medial ridge on the patellar articular surface serves as morphological reference for patellar alignment. It has been shown that proper positioning of the patellar implant with the medial ridge reduces the Q angle and helps in restoring kinematics post-surgery [45]. Beyond the measurements purely based on the patellar bone, there are additional focuses on the relative position of the patellar relative to the femoral trochlea, including patellar displacement and patellar tilt measured in the sunrise view, and patellar height assessed with a slight knee flexion in the sagittal view. These additional measurements serve as important indications for assessing extensor mechanism and patellar tracking.

Morphological considerations related to arthroplasty in the knee are not limited to just the morphology of proximal tibial and distal femur. Research efforts also expanded to the understanding of the anatomical shape of the tibial and femoral shaft and its impact on alignment and clinical outcomes related to the use of stemmed implants and intramedullary nailing. In the coronal plane, a normal "straight" femur shows no bowing of its shaft and a 3° valgus angle in the condylar surface with respect to the femoral mechanical axis, whereas the proximal tibial surface is at a corresponding 3° of varus with reference to the tibial mechanical axis [46–48]. However, a fair amount of bowing exists in the population, especially prevalent in the Asian ethnicities [49, 50]. With the use of intramedullary guide during surgery, the presence of lateral bowing can lead to varus alignment of the femoral component, and varus inclination of the tibia surface had clinical implications in gap balancing requiring increased medial release or femoral implant external rotation. In the sagittal plane, studies have shown that overlooking sagittal femoral bowing can cause improper femoral implant sizing during conventional TKA and notching in navigated mechanically aligned TKA [51]. These surgical mistakes heighten the risk of excessive flexion of the femoral implant, limited knee extension, compromised fixation of stemmed femoral implant, postoperative supracondylar femoral fracture, and polyethylene post wear caused by cam-post impingement in posterior stabilized (PS) TKA [51–53]. Thereupon, care needs to be taken during intramedullary guided procedure as the bowing morphology of the femur and tibia may lead to alignment outliers that are detrimental to the clinical outcomes and longevity of the surgery [54, 55].

With the advances of computational methods, the investigation of knee morphology progressed into the era of population-based analysis and is no longer restricted to limited number of discrete measurement metrics. One powerful tool for such analysis is statistical shape modeling. Shape models provide an analytic tool for the study of anatomy such as individual bone types in the knee or even the entire knee joint complex. By disseminating a complex bony anatomy into a mathematical formula using a set of principal components, the variability in morphology across can be understood with the identification of the primary driving mode of variations. Morphological data from the application of this advanced tool has been applied successfully in detecting variability in native distal femoral and proximal tibial morphology [56] and TKA tibial resection surface [57] across populations as inputs to drive anatomical designs in the knee, including tibial plates for internal fracture fixation, fibular plates, and TKA tibial base plate [58, 59]. Several studies characterized the entire joint anatomy by looking at individual bones coupled with their relative position to each other. Using one shape model, Fitzpatrick et al. quantified the combined variability of the resected profiles of the patella, femur, and tibia during TKA [60]. Some studies advanced the analysis to combine the morphology of the knee joint structure and limb alignment in the shape modeling, quantify variability due to morphology and relative alignment [61].

22.3 Gender Variations in Knee Morphology

With the expansion of knee arthroplasty from its western origin to around the world and increased application volume in genders, recurrent gender- and ethnic-based inferior outcomes were discovered which led to an extensive research. It has been realized that there are intrinsic differences in knee morphology across ethnics and genders that may in part explain the variable clinical outcomes.

Numerous studies have documented the differences between male and female knee morphology. Consistent trends have been reported that within any specific ethnic population, male knees are on average larger in size than the female knees in all dimensional measurements, while the gender differences found in knee shape are less prominent [37, 62–65]. In a 2012 study by Yan et al., the male knees showed significantly greater coronal dimensions of the trochlea than the female knees [63]. The authors suggested these dimensional discrepancies contributed to the higher prevalence of prosthetic overhang in women with some standard implants. Koh et al. revealed that although the posterior condylar offset was larger in the male knee compared to the female knee, the same trend in gender did not stand in the ratio between the sagittal AP shape of the knee. Female knees exhibited higher posterior condylar offset proportional to the total AP size of the distal femur than the male knees [62].

In a study carried out by Asseln et al., an extensive list containing 33 features of the femur and 21 features of the tibia were used to investigate gender differences [64]. The results demonstrated significant larger values in all linear dimensional measurements (size) but only selective angular measurements (shape). A systematic review of the PubMed database was performed on published studies on more than 9000 knees from four ethnic groups [65]. The key dimensions in the knee (ML and AP) were all shown to have higher values in males compared to females, while the differences in the aspect ratios were more subtle and variable. Several studies showed that when the dimensional measurements are normalized, gender-specific differences dissipate. Fehring et al. reported no significant gender difference in the height of femoral lateral condyle and nominal differences regarding the medial condyles [66].

Voleti et al. found gender-specific differences in femoral medial and lateral posterior condylar offsets. However, they disappeared after normalization by the condylar height [67]. Dai et al. used a comprehensive list of morphometric to quantify the size and shape of the tibial TKA resection surface [37]. Although it was revealed that male knees were bigger in all size metrics in each of the three ethnic groups investigated (Caucasian, Indian, and Japanese), the correlation between the ML and AP dimensions shared very similar slopes between the two genders, suggesting limited difference between the two genders in aspect ratio of the resection plateau [37]. Further statistical shape analysis in the same study revealed that the driving factor for the variability over served between male and female resided in the general size difference between the two genders, while in general shape remains constant.

As the knee size in females increases, the aspect ratio of femur decreases. However, in males, the aspect ratio remains constant irrespective of the knee sizes [68–70]. Therefore, it is necessary to implicate gender-specific implants to minimize the femoral overhang issue post implant. To put this into practice, orthopedic surgeons of Korea demonstrated that in cases where overhang was difficult to overcome while inserting traditional implants, the incidence of femoral component overhang was reduced by 34.6% by using the gender-specific implants [71].

22.4 Ethnic Variations in Knee Morphology

In the history of the application of knee arthroplasty, nearly all knee prostheses were originally designed based on the morphological features of western knees from primarily white Caucasian patients. Several studies have passed judgment that the tailor-made arthroplasty prostheses for Caucasian patients are not appropriate in cases with other ethnic background. Investigations that have detailed anthropometric differences according to ethnicity have primarily been focused between Caucasian and Asian populations [19,

56, 72], as well as numerous individual reports on ethnic-specific knee morphology [20, 21, 45, 73–76]. Caucasian knees have been shown to be generally larger than Asian knees [37, 56, 65, 73], which may give rise to the risk of implant oversize when used in Asian patients. In addition, for a given AP dimension, Caucasian knees have been shown to have a higher aspect ratio compared to Asian knees [19] (Fig. 22.1).

In a statistically defined shape analysis of the knee architecture, Mahfouz and his colleagues, identified differences in shape between the distal femur and proximal tibia with respect to the African American, Asian, and Caucasian [56]. Both the locations and magnitudes of morphological deviations of the distal femur and proximal tibia were identified during the paired comparison between the ethnicities investigated. Studies also showed considerable variations in normal alignment between ethnicities [49, 50, 77–79]. Asian population is reported to have more deviation in the angular alignment than Caucasian. In a 2008 study by Harvey et al., Asian knees were found to have a substantially more valgus anatomic axis, valgus condylar angles, and valgus condylar-plateau angles compared to the Caucasian knees [72]. Femurs in the Asian population also are substantially more tibial slope and externally rotated than Western patients [80, 81]. Thereafter, many Asian studies have found severe varus inclination in cases of advanced osteoarthritis with femoral lateral bowing and obliquity of the proximal tibial joint surface in knees [49, 50, 77–79].

The accumulated data by studies across geographic regions, along with the availability of advanced population-based analyses, provided a vast amount of knowledge to reveal gender and ethnic impact on knee morphology. Table 22.2 summarizes a collection of reported data on common measurements across gender and ethnic populations.

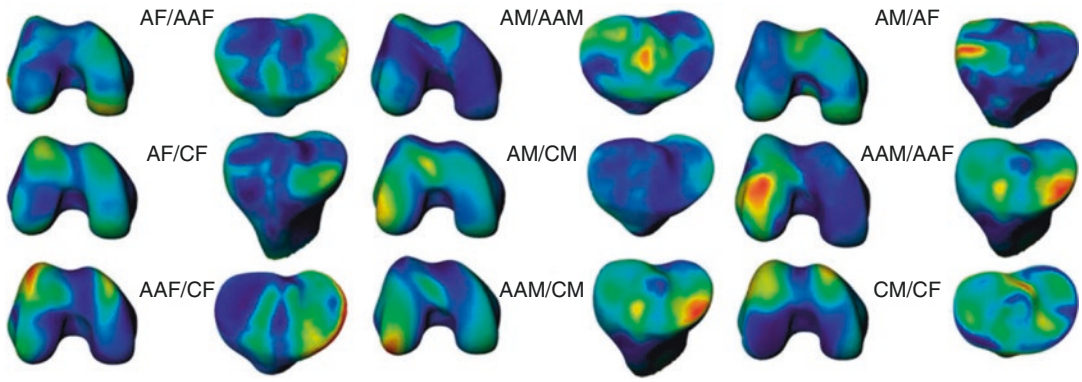

Fig. 22.1 The differences between high (red) and low (blue) global shape variations among gender and ethnic background portrayed by the second to ninth principal components are shown in this figure. *AF* East Asian Female, *CM* Caucasian male, *AAM* African American male, *AAF* African American Female [18]

Table 22.2 Summary of a list of common gender and ethnic specific morphological measurements in ML, AP, aspect ratio, etc. (N = No. of knees, S = No. of studies) [45, 65, 75, 76] Measures of Femoral AP (N = 360; S = 13)

	Males		Females		Both sexes	
Ethnicity	Mean	95% CI	Mean	95% CI	Mean	95% CI
White	64	60–69	59	54–64	62	57–66
Black	66	61–70	61	55–67	63	58–68
East Asian	61	57–66	56	52–60	59	54–63
Indian	61	45–77	55	39–70	59	42–73

Measurements in mm; p values of main effects: ethnicity (<0.001); sex (<0.001); interaction (0.954); white versus black (0.639), East Asian (<0.001), Indian (0.957); black versus white (0.639), East Asian (0.012), Indian (0.900); East Asian versus black (0.012), white (<0.001), Indian (0.999); Indian versus black (0.900), white (0.957), East Asian (0.999)

(continued)

Table 22.2 (continued)

A. Measures of Femoral mediolateral aspect ($N = 1884$; $S = 15$)

	Male		Female		Both sexes	
Ethnicity	Mean	95% CI	Mean	95% CI	Mean	95% CI
White	79	75–83	69	65–72	74	70–77
Black	71	65–77	67	60–75	69	64–74
East Asian	76	73–79	67	64–70	71	69–74
Indian	70	59–80	61	49–73	65	55–76

Measurements in mm; *p* values of main effects: ethnicity (0.167); sex (<0.001); interaction (0.564); black versus while (0.254), East Asian (0.560), Indian (0.458); black versus white (0.254), East Asian (0.738), Indian (0.911); East Asian versus black (0.738), while (0.560), Indian (0.670); Indian versus black (0.911), white (0.458), East Asian (0.670)

B. Measures of Femoral medial AP ($N = 2183$; $S = 8$)

	Male		Female		Both sexes	
Ethnicity	Mean	95% CI	Mean	95% CI	Mean	95% CI
White	65	61–68	59	55–62	62	58–65
Black	65	61–70	63	56–70	M	59–69
East Asian	60	57–64	56	52–59	58	54–62

Measurements in mm; *p* values of main effects: ethnicity (0.009); sex (0.004); interaction (0.156); while versus black (0.338), East Asian (0.012); black versus white (0.338), East Asian (0.022); East Asian versus black (0.022), white (0.012)

C. Determination of Femoral aspect ratio ($N = 4825$; $S = 14$)

	Male		Female		Both sexes	
Ethnicity	Mean	95% CI	Mean	95% CI	Mean	95% CI
White	1.22	(1.13–1.31)	1.17	(1.08–1.26)	1.20	(1.11–1.29)
Black	1.19	(1.09–1.29)	1.19	(1.08–1.26)	1.19	(1.02–1.37)
East Asian		(1.18–1.35)	1.23	(1.15–1.32)	1.25	(1.16–1.34)

P value of main effects: ethnicity (0.0002); sex (0.558); interaction (0.915); white versus black (0.996), East Asian (0.001); black versus white (0.996), East Asian (0.694); East Asian versus black (0.694), white (0.001)

D. Measures of Tibial AP ($N = 3553$; $S = 11$)

	Male		Female		Both sexes	
Ethnicity	Mean	95% CI	Mean	95% CI	Mean	95% CI
White	52	49–54	45	43–48	48	46–51
Black	53	48–58	48	43–53	50	46–54
East Asian	50	48–53	45	43–47	48	45–49
Indian	48	40–56	44	36–52	46	38–54

Measurements in mm: *p* values of main effects: ethnicity (0.401); sex (<0.001); interaction (0.662); white versus black (0.664), East Asian (0.646), Indian (0.904); black versus white (0.664), East Asian (0.409), Indian (0.722); East Asian versus black (0.409), white (0.646), Indian (0.969); Indian versus black (0.722), white (0.904), East Asian (0.969)

E. Measures of Tibial mediolateral aspect ($N = 4194$; $S = 14$

	Male		Female		Both sexes	
Ethnicity	Mean	95% CI	Mean	95% CI	Mean	95% CI
While	79	78–81	69	68–71	74	73–76
Black	80	76–83	67	63–70	73	71–76
East Asian	77	76–78	69	68–70	73	72–74
Indian	77	74–79	69	66–71	73	71–75

Measurements in mm; *p* values of main effects: ethnicity (0.039); sex (<0.001); interaction (0.013); while versus black (0.771), East Asian (0.036), Indian (0.361); black versus white (0.771), East Asian (0.984), Indian (0.990); East Asian versus black (0.984), while (0.036), Indian (1.000); Indian versus black (0.990), while (0.361), East Asian (1.000)

Table 22.2 (continued)

F. Measures of Tibial medial AP ($N = 3541$; $S = 12$)

	Male		Female		Both sexes	
Ethnicity	Mean	95% CI	Mean	95% CI	Mean	95% CI
White	53	51–55	47	45–49	50	48–52
Indian	51	48–53	45	42–53	48	45–50
East Asian	52	50–53	46	45–48	49	48–51

Measurements in mm; p values of main effects: ethnicity (0.096); sex (<0.001); interaction (0.466); white versus East Asian (0.598), Indian (0.079); East Asian versus white (0.598), Indian (0.287); Indian versus white (0.079), East Asian (0.287)

G. Determination of Tibial aspect ratio ($N = 1653$; $S = 5$)

	Male		Female		Both sexes	
Ethnicity	Mean	95% CI	Mean	95% CI	Mean	95% CI
White	1.57	1.42–1.73	1.54	1.38–1.69	1.55	1.40–1.71
Black	1.54	1.38–1.70	1.43	1.27–1.59	1.49	1.33–1.64
East Asian	1.53	1.38–1.69	1.54	0.39–1.70	1.54	1.39–1.69

P values of main effects: ethnicity (0.006); sex (0.003); interaction (0.005); while versus black (0.005), East Asian (0.382); black versus white (0.005), East Asian (0.057); East Asian versus black (0.057), white (0.382)

22.5 Additional Considerations Regarding Knee Morphology

Although disease progression or deformity in the knee may lead to alternation of its bony structure, most of the large-scale morphological studies still focused on healthy knees, possibility due to the challenges in obtaining sufficient number of specimens with controlled pathological conditions and other confounding factors of the patients. A number of studies made the effort to report on OA knee morphology. Mullaji et al. performed a radiographic analysis on Asian varus osteoarthritic (OA) knees with a healthy cohort as control [50]. The study discovered that compared to healthy knees, varus OA knees exhibited significantly lower condyle–mechanical axis angle and a higher deviation between femoral mechanical axis and the axis of the distal intramedullary canal. The evaluation of anatomic variations and their outcomes were studied on the operative techniques practiced in total knee arthroplasty (TKA). Nagamine [49] assessed anatomic variations specific to OA patients in six morphological parameters based on their preoperative AP radiographs and identified the signature of the medial OA knees as bowing of the femoral shaft and proximal tibia vara with lateral offset of the tibial shaft concerning the tibial plateau's center. Leveraging statistical shape modeling, Fitzpatrick et al. explored morphological variations in TKA resection geometries from OA patients, revealing the variation of size and shape with the tested population and highlighted the domination of size on resection morphology [60]. These disease-specific morphological measurements provided valuable insights regarding special considerations that worth attention in surgical treatments of the affected knee under clinical setting.

The most important and notable thing is that almost all analyses performed to aid the understanding of knee morphology under bony resection situation relative to a specific arthroplasty application were based on a single resection scenario. It is hard to ignore that as the nature of human manual work, the variability in surgical resections, especially from conventional instrumented cases, should be well expected under clinical setting. For example, during TKA resection, variation can exist both during visual and manual identification of the landmarks for the establishment of critical anatomical references and surgeon's preference in using a slight variable

definition of reference. Clinicians commonly believe that resections with a deviation within ±3° in alignment are acceptable, while the account of bone resected may be less under control depending on the reference point for resection depth, device thickness to match, and sometimes the quality of the bone. It still remains largely unclear how to properly interpolate and what difference should be expected when transfer the published morphological knowledge based on single resection scenario into clinical setting. Limited investigations have attempted to shed light on this topic.

In a computational study by Dai et al. [82], the influence of variabilities at each step of proximal tibial resections, aiming to quantify the influence of variability in landmark detection on resection parameters on TKA resections. One important finding was that landmark variability influenced key dimensions of the resected plateau by several millimeters, significant enough to impact clinical decisions based on morphology. The morphology of the proximal tibia at different levels of resection was studied by Nakamura et al. with the depth ranging from primary to revision TKA (10–25 mm) [83]. Deeper resection depth led to substantial internal rotation of the resection surface relative to the tibial shaft up to 23° in the range investigated, with significant changes in the aspect ratio. The authors cautioned surgeons to pay attention to morphological changes depending on the specific amount of bone taken from the patients. The existing limited reports suggested that currently knowledge on single resection scenario may not be entirely conclusive. The investigations need to be advanced further to fully understand the scope of impact caused by the involvement of surgical variability.

Many studies have been suggested that anatomical designs exhibited improved latero-posterior (LP) coverage than the symmetrical standard designs in the ML and MP dimensions [84]. For example, in TKA designs, whether there is a clear clinical advantage provided by asymmetric designs over the symmetric designs is still debated over. Dai et al. reported that tibial designs based on the anatomical structure are more durable with high alignment precision than tibial structures designed in accordance with symmetric and asymmetric framework. Wernecke and his associates also concluded that in asymmetrical implants, there is more LP coverage than symmetrical implants in rotational controlled MRI study [85, 86]. Yang et al. [15] reflects that asymmetric tibial components are more fitting than other designs because the medial and lateral tibial surfaces are asymmetrical. Therefore, other prosthetic components would not completely overlay the tibial surface leading to extensive lateral overhang or undersized medial component. The functionality and efficacy of both the designs can be fully unraveled only after methodical clinical studies.

22.6 Conclusion

As application of knee arthroplasty is on the rise, innumerable explorative research has been conducted to measure the anatomical features in the knee and identify associated gender and ethnic differences. Variations are detected by computational statistical methods for morphologic analysis. Considering these variations, the use of gender-specific and ethnic-specific implants may lead to positive outcomes after knee arthroplasties. These results may help surgeons and manufacturers to better understand their patient population and improve the fit of the designed implants. Further studies need to be carried out to acquire more evidences on the benefits offered by designs driven by morphological inputs and expand the knowledge of knee morphology and its implication in surgical technique and variabilities to address good long-term outcomes and patient satisfaction across the population.

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