Anatomical Variations of The Proximal Tibia and Their Surgical Implications

Dr. D. Ida Success[1]*, Dr. Durga Devi G.[2], Dr. Krishnaveni Sharath[3], Dr. P. R. Devaki[4], Priyanga A [5]

[1]Postgraduate, Department of Anatomy, Sree Balaji Medical College and Hospital (BIHER), Chennai, Tamil Nadu, India, Email: idasuccess23@gmail.com
[2]Professor and HOD, Department of Anatomy, Sree Balaji Medical College and Hospital (BIHER), Chennai, Tamil Nadu, India, Email: durgadevi2781@gmail.com
[3]Professor, Department of Anatomy, Sree Balaji Medical College and Hospital (BIHER), Chennai, Tamil Nadu, India, Email: veni@yahoo.com
[4]Professor and HOD, Department of Physiology, Sree Balaji Medical College and Hospital (BIHER), Chennai, Tamil Nadu, India, Email: drvaithee@gmail.com
[5]Tutor, Department of Anatomy, Sree Balaji Medical College and Hospital (BIHER), Chennai, Tamil Nadu, India, Email: priyangaamuthavel@gmail.com

Abstract

Introduction: The knee joint is a complex synovial structure frequently affected by osteoarthritis, often requiring surgical interventions such as Total Knee Arthroplasty (TKA) and Unicompartmental Knee Arthroplasty (UKA). Accurate morphometric data of the proximal tibia is essential for optimal implant design and surgical success.

Aim & Objectives: This study aimed to provide morphometric details of the upper end of the tibia for arthroplasty. Objectives included measuring anteroposterior (AP) and mediolateral (ML) diameters of tibial condyles, dimensions of the intercondylar area, and assessing side-related asymmetry.

Methodology: A total of 303 dry adult tibiae (201 right, 102 left) were analysed using digital vernier calipers. Parameters measured included AP and transverse diameters, intercondylar widths, circumference, and vertical distance to the tibial tuberosity. Statistical analysis was performed, with $p < 0.05$ considered significant.

Results: Significant bilateral asymmetry was observed. The medial condyle consistently showed larger AP dimensions, while the lateral condyle was shorter and more circular. The intercondylar area and transverse diameters also demonstrated side-related differences.

Conclusion: The study confirms bilateral and compartmental asymmetry of the proximal tibia, underscoring the need for population-specific and asymmetric tibial implants to improve arthroplasty outcomes.

Keywords: Tibial morphometry, Knee arthroplasty, Condylar asymmetry, Implant design.

Introduction

The knee joint is a complex synovial joint essential for weight-bearing and locomotion. Osteoarthritis is the most common knee pathology, often requiring surgical management. With aging populations and rising obesity, procedures such as total knee arthroplasty (TKA) and unicompartmental knee arthroplasty (UKA) have become standard. Success depends on precise prosthetic sizing and positioning to maintain joint stability and range of motion. In TKA, bone resection must match prosthetic thickness to ensure maximal coverage of the tibial plateau. Undersizing risks subsidence into cancellous bone, while oversizing causes soft tissue irritation. Proper implant selection is therefore critical to long-term survival of the prosthesis. (1-7)

UKA is increasingly used for unicompartmental arthritis, especially in elderly patients. Tibial components are more prone to complications than femoral ones, making accurate morphometric data essential. Proper sizing prevents implant collapse and soft tissue impingement, ensuring stability and longevity. Morphometrics, the quantitative study of shape, is central to orthopedic implant design. Measurements such as anteroposterior (AP) and mediolateral (ML) diameters of tibial condyles and the intercondylar area guide surgical planning and prosthesis development. These parameters are also valuable in anthropology and forensic science. (8-11)

A major challenge is that most prostheses are designed using Caucasian data. Asian populations, including Indian, Japanese, and Korean, often have smaller knees, leading to implant mismatch. This mismatch can cause mediolateral overhang or undersizing, highlighting the need for population-specific morphometric databases.Sexual dimorphism further influences tibial morphology. Males generally exhibit larger condylar dimensions than females, as shown in Indian and Thai studies. Gender-specific prosthetic designs could improve fit and outcomes, while also aiding forensic sex determination.(11,12)

The tibial aspect ratio (ML/AP) varies with knee size. Smaller knees often have different shape configurations, but many prosthetic systems maintain a constant ratio across sizes. This results in mismatch, particularly in female patients, where implants may be too wide mediolaterally. Adjusting aspect ratios to population data is crucial for optimal coverage.Symmetry of the tibial plateau remains debated. Anatomical studies reveal asymmetry between medial and lateral condyles, with the medial condyle typically longer AP and oval, while the lateral is shorter and circular. Designing asymmetric tibial components may improve fit, though symmetric designs remain common for cost reason. (12,13)

Population studies confirm that the medial condyle is generally larger than the lateral condyle. Indian, Nigerian, and Kenyan data consistently show longer AP dimensions medially, emphasizing its role in stability and load transfer. Prosthetic design must account for this to avoid soft tissue impingement.The lateral condyle, smaller than the medial, presents unique challenges. CT studies in Japanese and North Indian populations show higher ML/AP ratios laterally. Using medial-based prostheses on the lateral side risks under hang, underscoring the need for lateral-specific implants.(12.14)

The intercondylar area houses cruciate ligament attachments, making its morphometry vital for implant design. Indian populations show smaller AP lengths compared to Thai and Korean groups. These differences influence cruciate-retaining versus sacrificing prosthesis design.Measurement methods vary. Direct measurements on dry bones provide accurate baseline data, while CT and MRI allow in vivo analysis and 3D modeling. Radiographs, though useful, may suffer from projection errors. Combining direct and imaging methods strengthens morphometric databases.(15,16)

Overall, anatomical variability across populations and genders challenges the "one-size-fits-all" approach. Western-designed implants often mismatch Asian patients, leading to poor outcomes. Population-specific morphometric studies are essential to improve implant design, surgical success, and forensic applications.

Aim & Objectives

• The aim of this study is to provide morphometric details of upper end of tibia with for unicompartmental and total knee arthroplasty.

Study objective:

· To measure key morphometric parameters of the proximal end of the tibia, including: anteroposterior (AP) and mediolateral (ML) diameters of the medial and lateral condyles ,Dimensions of the intercondylar area .

· To assess side-related differences between right and left tibiae (if both sides are studied), identifying any significant asymmetry.

METHODOLOGY

Study Design and Setting This morphometric study was conducted on dry adult human tibiae obtained from the osteology collection of the Department of Anatomy, SBMCH. A purposive sampling method was employed to select the specimens for the study.

Sample Size and Selection A total of 303 tibiae were included in the study, consisting of a distribution of 201 right and 102 left bones. The specimens were screened based on specific inclusion and exclusion criteria to ensure data reliability.

• **Inclusion Criteria:** The study included adult dry human tibiae (age ≥ 18 years) with well-preserved proximal ends and clearly identifiable anatomical landmarks. All included bones were distinctly identifiable as either right or left.

• **Exclusion Criteria:** Specimens were excluded if they were damaged, deformed, or eroded to the extent that anatomical landmarks were unclear. Additionally, bones exhibiting pathological changes—such as osteoarthritis affecting the condylar surfaces, evidence of fractures, surgical implants, or congenital and acquired deformities—were removed from the study.

Data Collection and Tools All measurements were obtained using a digital vernier caliper and a measuring scale to ensure precision. Data were recorded in millimeters (mm). The study focused on the following anatomical dimensions of the proximal tibia:

1. **Anteroposterior (AP) Measurements:** The AP diameters were measured for the distinct compartments of the tibial plateau to assess the sagittal depth. This included the AP diameter of the lateral condyle, the AP diameter of the medial condyle, and the AP diameter of the intercondylar area.

2. **Transverse Measurements:** Transverse dimensions were evaluated to determine the width of the tibial plateau. Parameters included the overall transverse diameter of the upper end of the tibia and the specific transverse diameter of the medial condyle. The morphometry of the intercondylar area was further detailed by measuring its

width at three distinct levels: the anterior end, the middle, and the posterior end.
3. **Circumference and Vertical Dimensions:** To assess the overall bulk of the proximal tibia, the total circumference of the upper end was measured. Additionally, the vertical dimension was assessed by measuring the distance from the anterior upper end of the intercondylar region to the tibial tuberosity.
Statistical Analysis The data obtained were statistically analyzed and presented as Mean ± Standard Deviation (S.D). A comparative analysis was performed between the right and left tibiae for all measured parameters. Statistical significance was determined based on calculated p-values, with a p-value of less than 0.05 considered statistically significant

Results

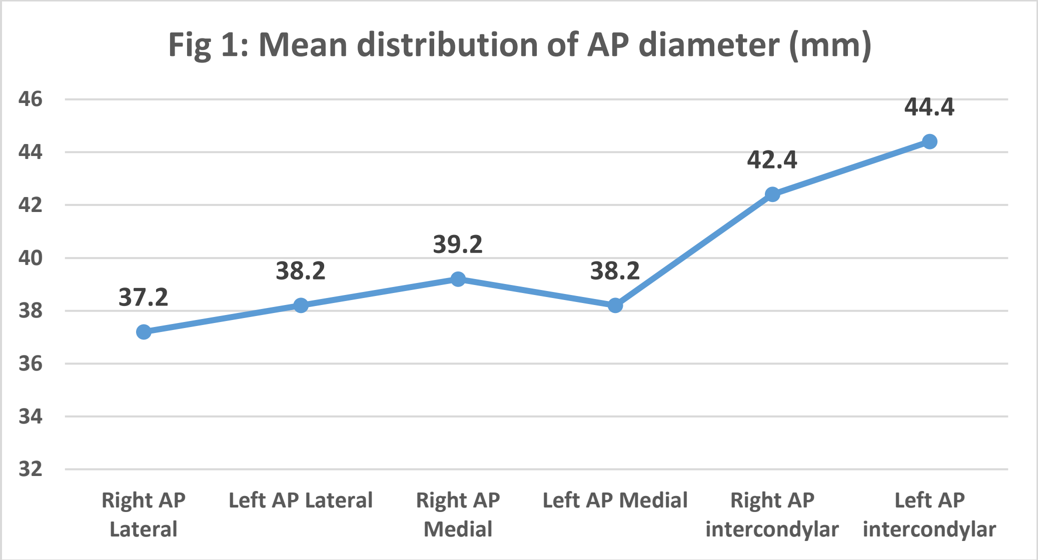
Anteroposterior (AP) Dimensions The morphometric analysis revealed statistically significant asymmetry between the right and left tibiae across all anteroposterior parameters measured. The mean AP diameter of the lateral condyle was significantly larger on the left side (38.0 ± 6.1 mm) compared to the right side (37.2 ± 5.1 mm) (*p=0.01*). In contrast, the AP diameter of the medial condyle was significantly larger on the right side (39.2 ± 5.01 mm) than on the left (38.2 ± 6.1 mm) (*p=0.02*). The intercondylar area also demonstrated significant variation, with the left side presenting a larger mean AP diameter (44.4 ± 4.5 mm) compared to the right (42.4 ± 6.2 mm) (*p=0.03*).
Transverse Dimensions Significant bilateral differences were observed in the overall transverse diameter of the proximal tibia. The mean transverse diameter was significantly greater on the left side (28.2 ± 5.2 mm) compared to the right (27.4 ± 4.1 mm) (*p=0.04*). While the medial condyle transverse diameter was larger on the right side (28.1 ± 6.2 mm) compared to the left (27.1 ± 5.2 mm), this difference did not reach statistical significance (*p=0.06*).
Regarding the intercondylar area widths, the anterior aspect showed a significant difference, measuring 26.5 ± 5.01 mm on the left versus 25.2 ± 7.01 mm on the right (*p=0.04*). The middle and posterior transverse diameters of the intercondylar area did not exhibit statistically significant asymmetry (*p=0.07* and *p=0.12*, respectively).
Circumference and Vertical Dimensions The total circumference of the proximal tibia showed a marginally significant difference between sides (*p=0.05*), measuring 18.5 ± 1.5 mm on the left side and 18.3 ± 1.8 mm on the right side. The vertical distance from the anterior upper end of the intercondylar area to the tibial tuberosity showed no statistically significant difference (*p=0.21*), with mean values of 3.6 ± 0.7 mm on the right and 3.4 ± 0.6 mm on the left.

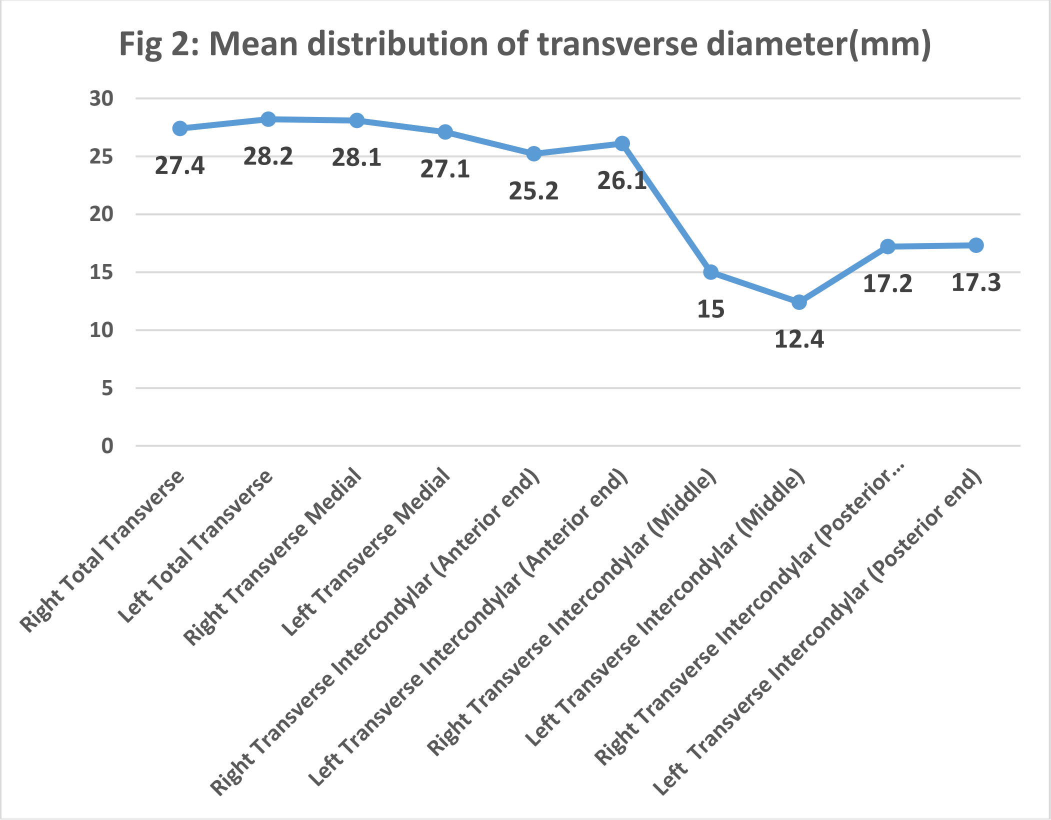
Table 1: Comparative Morphometric Values of Right and Left Tibiae

Parameter	Right Side (Mean ± SD)	Left Side (Mean ± SD)	p-value
AP Dimensions (mm)			
AP Lateral	37.2 ± 5.1	38.2 ± 6.1	0.01*
AP Medial	39.2 ± 5.01	38.2 ± 6.1	0.02*
AP Intercondylar	42.4 ± 6.2	44.4 ± 4.5	0.03*
Transverse Dimensions (mm)			
Total Transverse	27.4 ± 4.1	28.2 ± 5.2	0.04*
Transverse Medial	28.1 ± 6.2	27.1 ± 5.2	0.06
Transverse Intercondylar (Ant)	25.2 ± 7.01	26.5 ± 5.01	0.04*
Transverse Intercondylar (Mid)	15.0 ± 6.2	12.4 ± 2.0	0.07
Transverse Intercondylar (Post)	17.2 ± 4.1	17.3 ± 3.7	0.12

Other Dimensions (mm)			
Total Circumference	18.3 ± 1.8	18.5 ± 1.5	0.05*
Vert. Dist. to Tuberosity	3.6 ± 0.7	3.4 ± 0.6	0.21

**Indicates statistical significance (p ≤ 0.05)*





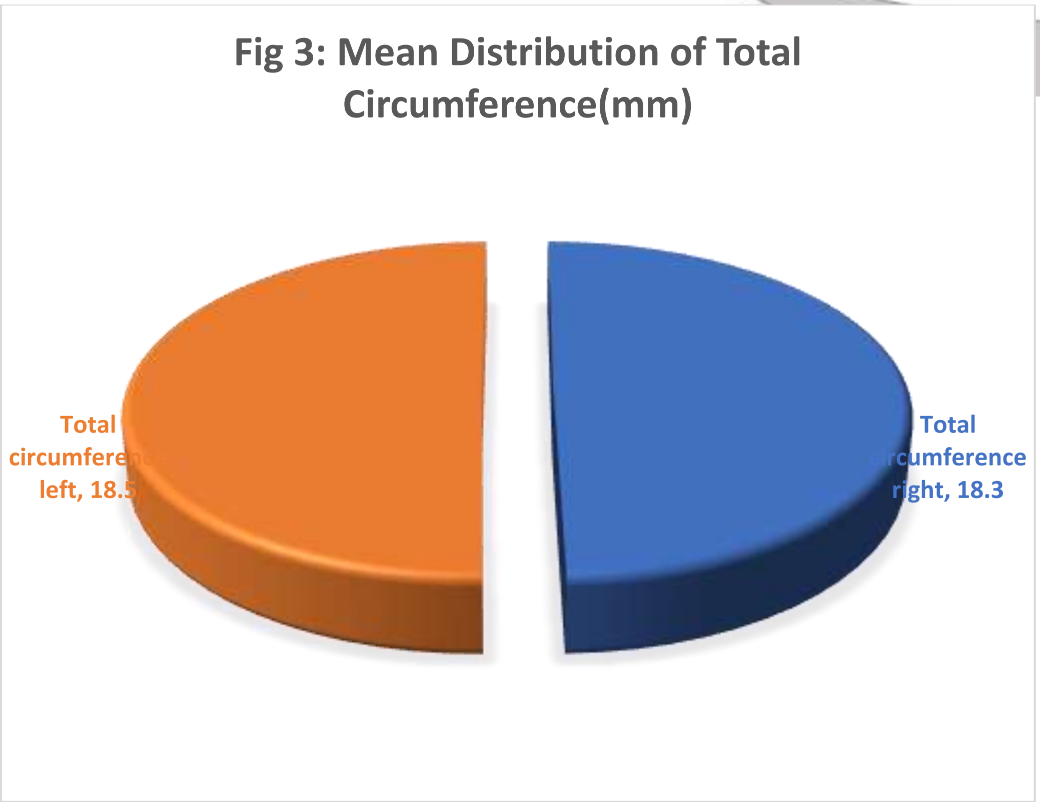


Fig 3: Mean Distribution of Total Circumference(mm)

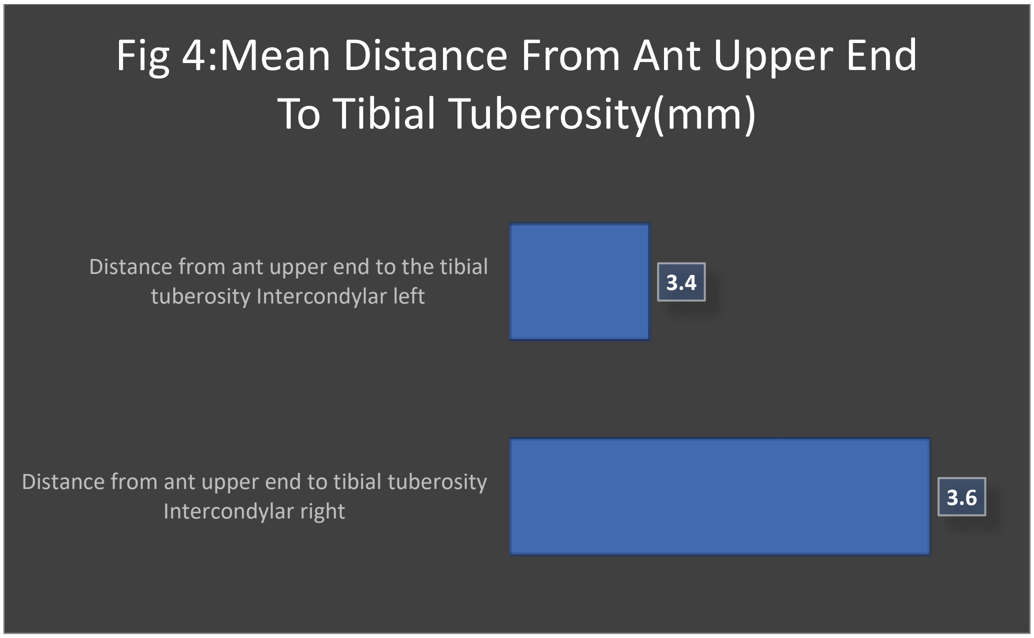


Fig 4:Mean Distance From Ant Upper End To Tibial Tuberosity(mm)

Discussion

The present study establishes comprehensive morphometric data for the proximal tibia, revealing statistically significant asymmetries between the right and left sides, as well as distinct differences between the medial and lateral condyles. A key finding of this investigation was that the anteroposterior (AP) diameter of the medial condyle was significantly larger than that of the lateral condyle, a pattern consistent with the inherent morphological asymmetry of the tibial plateau. This observation aligns with previous research by Srivastava et al. and Gandhi et al., who also reported that the medial condyle consistently exhibits greater AP and transverse dimensions compared to the lateral condyle. Understanding this asymmetry is critical because using symmetric tibial components for inherently asymmetric surfaces can lead to posterolateral overhang, which may impinge on the popliteus tendon and cause residual pain.(17,20)

Bilateral Variations in Tibial Morphometry

In analysing the bilateral variations, our study found statistically significant differences between the right and left tibiae across multiple parameters, including the AP diameters of both condyles and the intercondylar area. Specifically, the AP diameter of the medial condyle was larger on the right side, whereas the AP diameter of the lateral condyle was larger on the left side. This contrasts slightly with the findings of Gandhi et al., who noted that while dimensions were generally greater on the right side, the bilateral differences were not statistically significant. Similarly, Agichani et al. found no statistically significant difference in AP and transverse diameters between the right and left sides in a Central Indian population. The significant bilateral asymmetry observed in our study suggests that the side of the limb should be a critical factor in preoperative templating and implant selection to ensure optimal bony coverage.(6)

Intercondylar Area Morphology and Prosthetic Design

The dimensions of the intercondylar area also displayed significant variability, with the current study recording a larger AP diameter on the left side compared to the right. This area is clinically vital as it houses the cruciate ligaments, and its morphology correlates with the design of cruciate-retaining or substituting prostheses. In contrast to our findings, Agichani et al. reported that the AP diameter of the intercondylar area was greater on the right side, although their transverse measurements were larger on the left. The preservation of the intercondylar area dimensions is essential during TKA to maintain normal knee kinematics and ensure that the implant does not impinge on the intercondylar notch, which could restrict the range of motion.(4)

When comparing the morphometric data of the present study with international populations, distinct racial variations become evident. The dimensions obtained in our Indian population sample are generally smaller than those reported for Caucasian populations. For instance, studies on French and Western populations have consistently reported larger mean AP and transverse diameters for both tibial condyles compared to the values observed in our study and other Indian studies. This discrepancy highlights the potential risks of using "off-the-shelf" prostheses designed based on Western anthropometric data for Asian patients, as this often leads to component mismatch, most commonly oversizing.

Challenges of Lateral Condyle Geometry

The issue of implant mismatch is further complicated by the geometry of the lateral plateau. Our data supports the observation that the lateral condyle is shorter in the AP dimension compared to the medial condyle. Kamenaga et al., in a study on a Japanese population, emphasized that the lateral compartment has a lower AP length and a higher mediolateral-to-anteroposterior ratio compared to the medial side. Consequently, they strongly recommended the use of compartment-specific implants, such as the Oxford Fixed Lateral tibia, over standard implants to improve coverage and reduce the risk of underhang or overhang. This is particularly relevant for Unicompartmental Knee Arthroplasty (UKA), where precise sizing is paramount to prevent subsidence and loosening.(16)

Transverse Dimension Asymmetry

Transverse dimensions in the current study also showed significant bilateral asymmetry, with the total transverse diameter being significantly greater on the left side. This finding differs from Chaitra et al., who found that while the left medial condyle was slightly wider, the overall differences between sides were less pronounced. The transverse width is a limiting factor in achieving maximal implant coverage; inadequate coverage can transfer load to the weaker cancellous bone, leading to implant collapse, while excessive width causes soft tissue irritation. Therefore, the statistically significant variation in transverse width observed in our study reinforces the need for a wide range of tibial baseplate sizes to accommodate the diverse anatomical profiles within the population.(14)

Another important consideration highlighted by our findings is the variability in tibial morphometry across different ethnic groups. The smaller dimensions observed in our Indian population compared to Western cohorts reinforce the need for region-specific implant design. Studies from Thailand and Korea have similarly demonstrated that Asian knees are generally narrower mediolaterally and shorter anteroposteriorly than Caucasian knees, which can result in frequent component mismatch when Western-based prostheses are used. (19,20). This mismatch not only compromises implant coverage but also increases the risk of subsidence and loosening, underscoring the necessity for manufacturers to incorporate diverse anthropometric datasets into prosthetic development.

Implications of Medial–Lateral Condyle Asymmetry

Furthermore, the asymmetry between medial and lateral condyles observed in our study has direct implications for implant geometry. The medial condyle consistently demonstrated larger AP dimensions, while the lateral condyle was shorter and more circular, a finding corroborated by Japanese and Indian morphometric studies.(7,8,14) Using symmetric tibial components on inherently asymmetric plateaus may lead to posterolateral overhang, impingement of the popliteus tendon, and altered knee kinematics. This supports the growing advocacy for asymmetric tibial baseplates, which better replicate native anatomy and improve functional outcomes. Future implant design should therefore prioritize compartment-specific adaptations to minimize mismatch and enhance longevity of knee arthroplasty.

Sexual Dimorphism in Tibial Morphometry

Sexual dimorphism is another factor frequently cited in tibial morphometry literature, with male dimensions consistently exceeding those of females. While the current dataset focused on bilateral and compartmental asymmetry, the literature suggests that gender-specific sizing could further refine implant fit. Gandhi et al. demonstrated that all morphometric parameters were statistically significantly larger in males compared to females. Although our current results highlighted side-to-side differences, incorporating gender-specific data in future prosthetic designs could further reduce the incidence of component mismatch seen in female patients who receive standard implants.(20)

In conclusion, this study confirms that the proximal tibia exhibits significant bilateral and compartmental asymmetry, with the medial condyle being morphologically distinct from the lateral condyle. The measurements obtained are consistent with other studies on Asian populations but are smaller than those of Western populations, underscoring the necessity for population-specific prosthetic designs. These findings provide valuable baseline data for orthopaedic surgeons and manufacturers to design and select tibial components that replicate normal knee kinematics, thereby improving the longevity and functional outcomes of knee arthroplasty in the local population.

Conclusion

The present study provides detailed morphometric baseline data for the proximal tibia, confirming the existence of significant bilateral and compartmental asymmetry. The analysis demonstrated that the medial condyle is morphologically distinct from the lateral condyle, generally exhibiting larger anteroposterior dimensions. Furthermore, statistically significant differences were observed between the right and left tibiae across multiple parameters, including the anteroposterior diameters of the intercondylar area and both condyles. These findings challenge the efficacy of using symmetric tibial components and underscore the anatomical complexity that must be navigated during knee arthroplasty.

The clinical relevance of these anatomical variations is profound, particularly for Total Knee Arthroplasty (TKA) and Uni compartmental Knee Arthroplasty (UKA). The prevalent use of symmetric prostheses for inherently asymmetric tibial plateaus poses a high risk of component mismatch. Specifically, the shorter anteroposterior dimension of the lateral condyle increases the susceptibility to posterolateral overhang if a standard symmetric implant is used. Such mismatch can lead to soft tissue impingement, residual pain, and altered knee kinematics, whereas under sizing to avoid overhang may result in inadequate bony coverage and subsequent implant subsidence.

Additionally, this study highlights distinct racial variations in tibial morphometry. The dimensions recorded in this Indian population subset were generally smaller than those reported in Western Caucasian populations. This discrepancy indicates that "off-the-shelf" prostheses designed based on Western anthropometric data may not be suitable for Asian patients, leading to a higher incidence of component mismatch. The data reinforces the observation that anatomical profiles are population-specific, necessitating the development of implants that cater to the specific morphometric characteristics of the local demographic.

In light of these findings, it is imperative that orthopaedic surgeons and implant manufacturers consider both the asymmetry of the tibial plateau and population-specific dimensions when designing and selecting prostheses. The significant side-to-side and compartment-specific differences observed in this study advocate for the increased use of anatomic or asymmetric tibial components to optimize bony coverage and restore normal joint mechanics. Future research and implant design should prioritize these morphometric nuances to enhance the longevity of the prosthesis and improve functional outcomes for patients undergoing knee arthroplasty.

Conflicts of Interests: No
Ethics Committee Approval Obtained:002/SBMCH/IHEC/2024/2232
Informed Consent Obtained from The Subjects Involved In The Study: Yes
Funding: Self-Funding

References

1. Anurag, Gupta S. Morphometric Study of the Proximal End of Tibia. Int J Acad Med Pharm. 2023;5(3):1736-1738.
2. Eboh DEO. Morphometric Anatomy of the Tibia Plateau in Nigerians. Ethiop J Health Sci. 2021;32(1):155-160.
3. Kwak DS, Surendran S, Pengatteeri YH, Park SE, Choi KN, Gopinathan P, Han SH, Han CW. Morphometry of the proximal tibia to design the tibial component of total knee arthroplasty for the Korean population. The Knee. 2007;14:295–300.
4. Verma S, Bharti S, Nakhate M, Moore R. Osteometric Morphometry of the Proximal Tibial End in the Indian Population from a Forensic Perspective, Highlighting its Clinical Significance. Int J Acad Med Pharm. 2023;5(6):1226-1230.
5. Kaur H, Mishra AB, Ram kumar A, Gandhi S. Proximal End of Tibia: Its Morphometry and Clinical Significance. Paripex - Indian Journal of Research. 2017;6(2).
6. Agichani SR, Medhi B, Harioudh SK. A Cross Sectional Study to Assess Morphometry of Upper End of 80 Cadaveric Tibiae in a Tertiary Care Centre of Central India. J Evid Based Med Healthc. 2021;8(30):2714-2718.
7. Gupta C, Kumar J, Kalthur SG, D'souza AS. A morphometric study of the proximal end of the tibia in South Indian population with its clinical implications. Saudi J Sports Med. 2015;15:166-9.
8. Anderson AF, Anderson CN, Gorman TM, Cross MB, Spindler KP. Radiographic Measurements of the Intercondylar Notch: Are They Accurate? Arthroscopy. 2007;23(3):261-268.
9. Mukhia R, Poudel PP, Bhattarai C, Timsina S. Morphometric Study of Proximal end of Femur of Nepalese People. Nepal Journal of Medical Sciences. 2019;4(1):9-14.
10. Moghtadaei M, Moghimi J, Farahini H, Jahansouz A. Morphology of proximal tibia in Iranian population and its correlation with available prostheses. Med J Islam Repub Iran. 2015;29:225.
11. Contractor JB, Umraniya B, Singh P. Morphometric analysis of proximal femur in Indian population and its implications in Total Hip Arthroplasty. Indian J Clin Anat Physiol. 2024;11(1):27-31.
12. Uehara K, Kadoya Y, Kobayashi A, Ohashi H, Yamano Y. Anthropometry of the Proximal Tibia to Design a Total Knee Prosthesis for the Japanese Population. J Arthroplasty. 2002;17(8):1028-1032.
13. Pooja B, Babita P, Sabita M. Morphometric study of proximal end of tibia with its clinical implications in North Indian population. J Evolution Med Dent Sci. 2018;7(23):2801-2806.
14. Chaitra D, Pai D, Rathnakar P, Remya K. Morphometric Study of Upper End of Tibia in Dakshina Kannada Population. J Evolution Med Dent Sci. 2020;9(15):1252-1255.
15. Umer M, Sepah YJ, Khan A, Wazir A, Ahmed M, Jawad MU. Morphology of the proximal femur in a Pakistani population. Journal of Orthopaedic Surgery. 2010;18(3):279-81.
16. Kamenaga T, Hiranaka T, Hida Y, Fujishiro T, Okamoto K. Morphometric analysis of medial and lateral tibia plateau and adaptability with Oxford partial knee replacement in a Japanese population. Journal of Orthopaedic Surgery. 2020;28(2):1–6.
17. Srivastava A, Yadav A, Thomas RJ, Gupta N. Morphometric Study of Tibial Condylar area in the North Indian Population. JMSCR. 2014;2(3):515-519.
18. Khurshid N, Afza R. Morphometric Study of Upper End of Tibia: A Study Done at SKIMS Medical College Srinagar. Int J Sci Res. 2019;8(8):9-10.
19. Phombut C, Rooppakhun S, Sindhupakorn B. Morphometric measurement of the proximal tibia to design the tibial component of total knee arthroplasty for the Thai population. J Exp Orthop. 2021;8:118.
20. Zalawadia AZ, Patel SM. Morphometric Study of Upper End of Tibia in Gujarat Region and its Clinical Implication in Knee Arthroplasty. Int J Anat Res. 2018;6(1.1):4871-4875.