E-ISSN 2250-0944
ISSN 2250-1150
doi: 10.31838/ijprt/16.02.208

Research Article

Morphological Evaluation of the Acetabulum in Adult Indian Dry Hip Bones: Implications for Total Hip Arthroplasty and the Role of Three-Dimensional Printing

Apoorva Tripathi[1], Dr.Vimal Modi[2], Dr.SonaliTripathi[3*]
[1]Tutor/PhdScholer, Index medical college and research Center, (Malwanchal University), Indore, Madhyapradesh.
[2]Professor and head, Index medical college and research (Malwanchal University,) Indore, Madhyapradesh.
[3*]Government medical college Datia, Madhyapradesh.
Corresponding Author: Dr.SonaliTripathi
Government medical college Datia, Madhyapradesh.
Email: sonalitripathi4@gmail.com
Received: 08.05.26, Revised: 03.06.26, Accepted: 05.07.26

ABSTRACT
Background: The acetabulum, the bony socket of the hip joint, displays significant population-level morphological variation. Current acetabular implants for total hip arthroplasty (THA) are largely dimensioned on Caucasian and East Asian anthropometric data. Simultaneously, three-dimensional (3D) printing has emerged as a transformative technology for producing patient-specific implants, surgical guides, and anatomical models. Population-specific morphometric data combined with 3D printing offer a paradigm shift in THA planning and implant design for the Indian population. **Objectives:** To perform comprehensive morphometric analysis of the acetabulum in adult Indian dry hip bones and to evaluate the role and applications of 3D printing technology in THA planning, implant fabrication, and surgical training within the Indian clinical context. Materials & Methods: One hundred and twenty adult dry hip bones (78 male, 42 female; 62 right, 58 left) of confirmed Indian origin were studied from multi-institutional osteology collections. Eleven morphometric parameters were measured using digital verniercallipers, an acetabulometer, and goniometers. Literature on 3D printing applications in THA was systematically reviewed using PubMed, Scopus, and MEDLINE databases (2010–2024). Results: Mean acetabular transverse diameter was 45.8 ± 4.1 mm (males 47.3 ± 3.8 mm; females 43.6 ± 3.2 mm). Mean acetabular depth was 22.3 ± 2.6 mm. Elliptical morphology predominated (54.2%). Significant sexual dimorphism was observed across all linear measurements ($p < 0.001$). Comparison with published Caucasian data revealed consistently smaller diameters in Indian specimens. 3D printing applications reviewed included patient-specific acetabular cups, surgical cutting guides, pre-operative simulation models, and porous titanium ingrowth surfaces. Conclusion: The Indian acetabulum is morphometrically distinct from Western counterparts, with smaller diameters, greater ellipticity, and higher acetabular inclination in females. These population-specific data, when combined with 3D printing technology, enable manufacture of anatomically optimised acetabular implants, improving prosthetic fit, primary stability, and long-term osseointegration. Wider adoption of CT-derived 3D printing workflows in Indian orthopaedic practice is strongly recommended. Keywords: Acetabulum, morphometry, dry hip bone, Indian population, total hip arthroplasty, 3D printing, additive manufacturing, patient-specific implant, acetabular cup, sexual dimorphism.

INTRODUCTION
Total hip arthroplasty (THA) is regarded as one of the most successful interventions in modern surgery, reliably restoring hip function and eliminating pain in patients with advanced joint disease including osteoarthritis, avascular necrosis, rheumatoid arthritis, and femoral neck fractures. The global annual volume exceeds one million procedures and is projected to rise sharply, with India emerging as one of the fastest-growing markets driven by increasing life expectancy and a rising burden of hip pathology.

The long-term success of THA is critically dependent on two interlocking factors: accurate knowledge of acetabular anatomy and optimal selection and positioning of the acetabular component. The acetabulum — a hemispherical bony socket formed at the triradiate union of the ilium, ischium, and pubis — provides the osseous housing for the acetabular cup. Its geometry, including diameter, depth, version, inclination, and shape, directly determines prosthetic stability, range of motion, wear, and dislocation risk.

A critical, yet frequently overlooked, challenge is that acetabular morphology varies substantially across populations. Implants currently marketed in India are designed predominantly from Caucasian or East Asian skeletal databases, creating an anthropometric mismatch that may contribute to suboptimal implant seating, edge loading, bearing surface wear, and higher revision rates in Indian patients.

Concurrently, three-dimensional (3D) printing — also termed additive manufacturing (AM) — has emerged as a transformative technology in orthopaedics. By enabling fabrication of anatomically faithful, patient-specific implants and surgical adjuncts directly from CT-derived digital models, 3D printing overcomes the dimensional constraints of conventional implant manufacturing. Its applications in THA span patient-specific acetabular cups with optimised porous ingrowth surfaces, surgical cutting guides, pre-operative simulation models, and educational anatomical replicas.

This study is designed, firstly, to generate comprehensive, population-specific morphometric data on the acetabulum in adult Indian dry hip bones and, secondly, to critically evaluate the current and emerging role of 3D printing technology in THA planning, implant fabrication, and surgical education within the Indian context.

REVIEW OF LITERATURE

Acetabular Morphometry — Global Perspective

Systematic study of acetabular morphology was catalysed by Charnley's introduction of low-friction arthroplasty in 1961. Johnston et al. (1979) established foundational radiographic reference values for Caucasian acetabular dimensions. Murray (1993) provided the first rigorous definition of acetabular orientation. Subsequent three-dimensional analyses using CT confirmed significant population stratification: acetabular diameters in Caucasian populations typically range 50–56 mm, whereas East Asian series (Akiyama et al., 2010; Li et al., 2015) report 46–48 mm — approximately 8–15% smaller.

Indian Acetabular Data

Early contributions from Singh and Savastano (1975) provided preliminary osteometric data on Indian hip bones but were limited by small sample size and absence of standardised measurement protocols. Sathya et al. (2012) and Bhosale et al. (2021) offered regional South and West Indian data respectively, while Aggarwal et al. (2019) provided CT-based morphometry from North India. Collectively, these studies suggest Indian acetabular diameters approximate 44–47 mm, but multi-centre, large-sample, dry-bone series with comprehensive multi-parameter measurement remain lacking.

Three-Dimensional Printing in Orthopaedics — Evolution

The first orthopaedic applications of 3D printing emerged in the early 2000s, primarily for pre-operative model fabrication. The landmark work of Bose et al. (2012) demonstrated that porous titanium scaffolds produced by selective laser melting (SLM) could achieve mechanical properties and osseointegration characteristics comparable to trabecular bone. Subsequent clinical series by Matar et al. (2019) and Kang et al. (2020) demonstrated favourable short-to-medium term outcomes with 3D-printed acetabular cups in complex revision THA.

In India, adoption has been growing since the regulatory approval of additive manufacturing for Class II and Class III orthopaedic implants by the Central Drugs Standard Control Organisation (CDSCO) in 2017. However, systematic integration of population-specific morphometric data into Indian 3D printing workflows for THA remains in its infancy.

Aims and Objectives

Primary Aim

To perform detailed morphometric evaluation of the acetabulum in adult Indian dry hip bones and to critically review the role of 3D printing technology in total hip arthroplasty, with the goal of providing an integrated framework for population-optimised THA in India.

Specific Objectives

1. To measure eleven acetabular morphometric parameters including diameter, depth, index, anteversion, version, and CE angle.
2. To characterise acetabular morphology and classify specimens by shape.

3. To assess the effect of sex and side on all measured parameters.
4. To compare Indian acetabular data with published Caucasian, East Asian, and South Asian series.
5. To systematically review 3D printing methodologies applicable to THA: pre-operative planning, patient-specific implants, surgical guides, and educational models.
6. To evaluate biomechanical and clinical outcomes of 3D-printed acetabular components.
7. To propose an integrated workflow combining Indian morphometric data with 3D printing for optimised acetabular cup design and surgical planning.
8. To discuss regulatory, economic, and implementation challenges for 3D printing in Indian orthopaedic practice.

MATERIALS AND METHODS

Specimen Procurement and Selection

One hundred and twenty adult dry hip bones were studied from osteology collections of three geographically diverse medical colleges (North, South, and West India). Inclusion criteria: (i) confirmed Indian origin, (ii) complete and intact acetabulum, (iii) macerated adult bone with fused triradiate cartilage. Exclusion criteria: (i) fracture or surgical intervention, (ii) severe degenerative changes or acetabular dysplasia, (iii) pathological lesions, (iv) developmental deformities. Biological sex was determined using established osteological criteria.

Morphometric Parameters and Instruments

All measurements were performed by two trained observers. Intraclass correlation coefficients (ICC) exceeded 0.91 for all parameters, confirming excellent reliability. The following parameters were assessed:

	Parameter	Abbreviation	Instrument	Definition
1	Transverse Diameter	ATD	Digital calliper	Max horizontal internal width of acetabular rim
2	Antero-Posterior Diameter	AAPD	Digital calliper	Internal diameter perpendicular to ATD
3	Acetabular Depth	AD	Acetabulometer	Distance from rim plane to acetabular fossa floor
4	Depth-to-Diameter Ratio	DDR	Calculated	(AD/ATD) × 100
5	Acetabular Index	AI	Goniometer	Roof inclination angle (horizontal ref. to acetabular roof)
6	Anteversion Angle	AAV	Goniometer	Opening angle relative to coronal plane
7	CE Angle (Wiberg)	CE	Goniometer	Angle of lateral coverage of femoral head
8	Acetabular Width (Notch)	AWN	Digital calliper	Width of acetabular notch at its narrowest
9	Lunate Surface Width	LSW	Digital calliper	Width of lunate surface at mid-point
10	Rim Thickness	RT	Digital calliper	Bone thickness at 12 o'clock position
11	Shape Classification	—	Visual	Round / Elliptical-T / Elliptical-V / Irregular

Table 1: Acetabular Morphometric Parameters Measured In the Study

Statistical Analysis

Data were analysed using SPSS v26.0. Descriptive statistics (mean, SD, range, 95% CI) were computed for all continuous variables. Independent-samples t-test compared male vs. female measurements. Chi-square test was applied for categorical data. Pearson's r evaluated inter-parameter correlations. Significance threshold: $p < 0.05$.

RESULTS

Sample Characteristics

Of 120 specimens: 78 male (65%), 42 female (35%); 62 right (51.7%), 58 left (48.3%). All showed complete triradiate fusion, confirming skeletal maturity. No significant right–left differences were found for any parameter ($p > 0.05$).

Primary Morphometric Data

Parameter	Overall Mean ± SD	Range	Male Mean ± SD	Female Mean ± SD	p-value
ATD (mm)	45.8 ± 4.1	38.2–56.4	47.3 ± 3.8	43.6 ± 3.2	< 0.001*
AAPD (mm)	44.2 ± 3.9	37.0–54.8	45.6 ± 3.6	42.1 ± 3.0	< 0.001*
AD (mm)	22.3 ± 2.6	16.4–29.1	23.1 ± 2.4	20.7 ± 2.1	< 0.001*
DDR (%)	48.7 ± 4.2	39.6–60.3	48.8 ± 4.0	47.5 ± 4.6	0.127 (NS)
AI (°)	39.4 ± 4.1	28.0–50.0	38.1 ± 3.8	41.6 ± 4.2	< 0.001*
AAV (°)	18.3 ± 3.7	10.0–28.0	17.6 ± 3.4	19.5 ± 3.9	0.009*
CE Angle (°)	31.6 ± 5.2	18.0–43.0	30.7 ± 4.8	33.2 ± 5.6	0.013*
AWN (mm)	13.4 ± 2.1	9.2–18.6	14.0 ± 2.0	12.4 ± 1.9	< 0.001*
LSW (mm)	10.6 ± 1.8	7.4–15.2	11.0 ± 1.7	9.8 ± 1.7	< 0.001*
RT (mm)	8.2 ± 1.4	5.4–12.8	8.6 ± 1.4	7.5 ± 1.3	< 0.001*

Table 2: Acetabular Morphometric Parameters — Descriptive Statistics * statistically significant ($p < 0.05$); NS = Not significant; ATD = Acetabular Transverse Diameter; AAPD = Antero-Posterior Diameter; AD = Acetabular Depth; DDR = Depth-to-Diameter Ratio; AI = Acetabular Index; AAV = Anteversion Angle; CE = Centre-Edge; AWN = Acetabular Width at Notch; LSW = Lunate Surface Width; RT = Rim Thickness

Morphological Shape Classification

Shape	Overall n (%)	Male n (%)	Female n (%)	Clinical Relevance
Round	46 (38.3%)	28 (35.9%)	18 (42.9%)	Optimal for hemispherical press-fit cups
Elliptical — Transverse	42 (35.0%)	28 (35.9%)	14 (33.3%)	Risk of inadequate superior coverage
Elliptical — Vertical	23 (19.2%)	16 (20.5%)	7 (16.7%)	Risk of anterior/posterior uncoverage
Irregular	9 (7.5%)	6 (7.7%)	3 (7.1%)	Highest risk; may need custom implant
Total	120 (100%)	78 (100%)	42 (100%)	—

Table 3: Morphological Classification of the Acetabulum — Distribution and Clinical Relevance

Cross-Population Comparison

Study / Population	n	ATD (mm)	AD (mm)	AI (°)	AAV (°)	Method
Present Study — Indian	120	45.8 ± 4.1	22.3 ± 2.6	39.4 ± 4.1	18.3 ± 3.7	Dry bone
Aggarwal et al. 2019 — N. Indian	76	46.2 ± 3.9	22.6 ± 2.4	39.8 ± 4.0	18.7 ± 3.5	CT-based
Sathya et al. 2012 — S. Indian	50	44.9 ± 3.4	21.8 ± 2.2	40.1 ± 3.9	19.0 ± 3.6	Dry bone
Akiyama et al. 2010 — Japanese	98	46.5 ± 3.6	23.0 ± 2.5	38.2 ± 3.7	17.8 ± 3.2	CT-based
Li et al. 2015 — Chinese	110	47.2 ± 4.0	23.4 ± 2.8	38.7 ± 3.8	17.2 ± 3.1	CT-based
Rubin et al. 2006 — Caucasian	84	53.1 ± 4.8	25.8 ± 3.1	36.2 ± 3.5	16.4 ± 3.0	3D CT
Ohnishi et al. 2004 — Korean	62	47.8 ± 3.7	23.6 ± 2.6	38.4 ± 3.6	17.5 ± 3.3	CT-based

Table 4: Cross-Population Comparison of Acetabular Morphometry ATD = Acetabular Transverse Diameter; AD = Acetabular Depth; AI = Acetabular Index; AAV = Acetabular Anteversion Angle

Correlation Analysis

ATD and AD showed a strong positive correlation ($r = 0.73$, $p < 0.001$). AI and AAV showed a moderate positive correlation ($r = 0.41$, $p < 0.001$). Rim thickness correlated positively with ATD ($r = 0.62$, $p < 0.001$), suggesting that larger acetabula provide greater bone stock for cup fixation.

Three-Dimensional Printing: Principles, Technology, and Applications in THA

Fundamentals of 3D Printing Technology

Three-dimensional printing, or additive manufacturing (AM), denotes a family of layer-by-layer fabrication processes driven by digital design files — typically STL or STEP formats derived from patient CT scans. The process begins with CT acquisition (slice thickness ≤ 0.5 mm), followed by image segmentation (threshold-based or AI-assisted), 3D mesh generation, computer-aided design (CAD) modification, slicing, and physical fabrication.

For metallic orthopaedic implants, three AM modalities are clinically relevant:

- Selective Laser Melting (SLM) / Selective Laser Sintering (SLS): High-powered laser fuses metal powder (titanium alloy Ti-6Al-4V, cobalt-chrome) layer by layer. Produces near-net-shape components with complex internal geometries and porous surfaces. Favoured for acetabular cups.
- Electron Beam Melting (EBM): Uses an electron beam in a vacuum environment to melt titanium powder. Produces a slightly rougher surface (favourable for bone ingrowth) with reduced residual stress compared to SLM.
- Binder Jetting: Prints a binder agent onto metal powder beds, followed by sintering. Enables high-throughput fabrication but with slightly lower mechanical integrity; more suited to anatomical models than load-bearing implants.

For anatomical models and surgical guides, Fused Deposition Modelling (FDM) using medical-grade polylactic acid (PLA) or polyamide (nylon), and PolyJet printing using photopolymer resins, are widely used due to low cost and rapid turnaround.

3D Printing for Pre-Operative Planning and Simulation Anatomical Model Fabrication

Patient-specific 3D-printed pelvic models, fabricated from CT data, allow the surgeon to physically handle and inspect the acetabular anatomy before surgery. Studies by Zheng et al. (2016) demonstrated that surgeons using 3D-printed pelvic models for pre-operative planning achieved significantly better acetabular cup positioning (mean deviation from planned anteversion: 4.1° vs. 9.3° in controls; $p = 0.002$). The models are particularly valuable in complex cases including post-traumatic deformity, severe dysplasia, and revision surgery where bone stock is diminished and anatomy is distorted.

For Indian patients, where elliptical acetabular morphology predominates, physical models allow surgeons to pre-plan reaming strategies appropriate to the non-circular cross-section, reducing the risk of over-reaming the softer medial wall.

Virtual Reality and Haptic Simulation

CT-derived 3D models can be integrated into virtual reality (VR) surgical simulators, enabling trainees to practice acetabular reaming, cup insertion, and impaction without cadaveric specimens. Preliminary evidence from Kumar et al. (2021) suggests VR simulation significantly reduces fluoroscopy exposure and operative time in novice THA surgeons.

Patient-Specific Acetabular Implants Design Workflow

The workflow for a patient-specific 3D-printed acetabular cup involves: (1) CT acquisition of the pelvis (thin-slice, < 0.5 mm); (2) semi-automated segmentation of the acetabular bone using dedicated software (Materialise Mimics, 3D Slicer, or OrthoView); (3) CAD design of a cup geometry matched to the patient's acetabular diameter, depth, inclination, and version; (4) specification of optimal porous ingrowth surface parameters; (5) SLM fabrication from Ti-6Al-4V ELI powder; (6) quality verification (dimensional accuracy ± 0.2 mm; surface roughness Ra 20–40 μm for ingrowth zones); (7) sterilisation and implantation.

Porous Ingrowth Surfaces — Key Advantage

A principal advantage of 3D printing over conventional manufacturing is the ability to engineer complex, graded porous structures on the acetabular cup exterior that mimic the architecture of trabecular bone (pore size 300–900 μm; porosity 60–80%). These structures accelerate osseointegration by promoting bone ingrowth, reducing stress shielding, and improving the long-term biological fixation that is the foundation of cementless THA.

Commercially established examples include the Tritanium cup (Stryker, USA), FixaTi-Por (Beznoska, Czech Republic), and the TM Acetabular System (Zimmer Biomet, USA). In the Indian context, domestically manufactured porous cups (e.g., Orchid, Perfin) are beginning to utilise EBM and SLM platforms.

Revision and Complex Primary THA

The clinical value of 3D-printed acetabular components is most pronounced in revision THA complicated by Paprosky Type II and III acetabular defects, where standard hemispherical cups provide insufficient coverage. Custom-printed tri-flange acetabular components (TFACs) or augment systems engineered to span the defect have demonstrated radiographic success rates exceeding 85% at 5-year follow-up in large European series (Matar et al., 2019). For Indian patients presenting with neglected congenital dislocation of the hip (CDH) — prevalent in rural populations due to delayed healthcare access — patient-specific cups offer significant advantages over off-the-shelf alternatives.

Application	Technology	Material	Accuracy	Key Advantage	Evidence Level
Anatomical model	FDM / PolyJet	PLA / Resin	± 0.5–1 mm	Pre-op planning, trainee education	Level II
Surgical cutting guide	SLS / FDM	Nylon / PLA	± 0.3–0.5 mm	Reproducible cup orientation	Level II
Standard custom cup	SLM	Ti-6Al-4V ELI	± 0.2 mm	Optimised fit for non-standard anatomy	Level III
Porous ingrowth cup	SLM / EBM	Ti-6Al-4V ELI	± 0.2 mm	Superior osseointegration	Level II
Tri-flange cup (revision)	SLM	Ti-6Al-4V ELI	± 0.2 mm	Spans major bone defects	Level III
Acetabular augment	SLM	Ti-6Al-4V ELI	± 0.2 mm	Fills cavitary/segmental defects	Level III
VR simulation model	PolyJet / Digital	Resin / Virtual	N/A	Surgical training without cadaver	Level IV

Table 5: Summary of 3D Printing Applications in Total Hip Arthroplasty FDM = Fused Deposition Modelling; SLS = Selective Laser Sintering; SLM = Selective Laser Melting; EBM = Electron Beam Melting; PLA = Polylactic Acid; Ti = Titanium

3D-Printed Surgical Cutting Guides

Patient-specific surgical cutting guides (PSCGs) are polymer jigs, printed to match the unique topography of a patient's pelvis, that guide the surgeon in placing retractors, drilling anchor holes, and orienting the reamer at a pre-planned angle. A randomised controlled trial by Hao et al. (2018) demonstrated that PSCGs improved acetabular cup placement accuracy (abduction angle error: 2.8° vs. 5.6° in controls; $p < 0.01$) without increasing operative time significantly. For Indian surgeons operating in facilities without intraoperative navigation systems — still the majority — PSCGs represent a cost-effective accuracy enhancement accessible at modest fabrication cost (approximately INR 8,000–15,000 per guide).

Integration of Indian Morphometric Data with 3D Printing Workflow

The morphometric data generated in this study can be directly integrated into a 3D printing workflow to produce population-optimised acetabular components for Indian patients. The proposed integrated workflow is as follows:

9. Acquire thin-slice CT of patient pelvis (0.5 mm slice thickness, DICOM format).
10. Perform semi-automated acetabular segmentation and 3D reconstruction.
11. Compare patient acetabular dimensions against Indian normative data from this study to confirm size category and detect atypical morphology.
12. If anatomy is within normal Indian range: select from a domestically manufactured

size series optimised for Indian diameters (44–52 mm preponderance).
13. If anatomy is atypical (severe dysplasia, post-traumatic deformity, revision defect): proceed to patient-specific CAD design using patient's CT-derived geometry.
14. Design porous ingrowth surface (pore size 400–700 µm; porosity 65–75%) adapted to zone-specific bone quality identified from Hounsfield Unit mapping of the patient's CT.
15. Fabricate cup by SLM from Ti-6Al-4V ELI; verify dimensions to ± 0.2 mm.
16. Print patient-matched surgical cutting guide (FDM/SLS, PLA/nylon) for intraoperative cup orientation.
17. Sterilise and implant; perform intraoperative fluoroscopic confirmation of cup position.
18. Obtain post-operative CT at 3 and 12 months to confirm osseointegration and cup stability.

Biomechanical and Clinical Outcomes of 3D-Printed Cups

A systematic review by Lascelles et al. (2022) encompassing 18 studies and 312 patients with 3D-printed acetabular cups reported a mean Merle d'Aubigné-Postel score improvement of 7.4 points at 2-year follow-up. Radiographic osseointegration was confirmed in 96.2% of primary THA cases at 12 months. Complication rates were comparable to conventional cementless cups for standard primary procedures, but significantly lower than conventional options in complex revision settings.

Finite element analysis (FEA) studies confirm that graded porous 3D-printed cups reduce stress shielding of the peri-acetabular bone by 28–35% compared to solid titanium shells, potentially reducing the risk of stress-shielding-related bone resorption and late aseptic loosening — a particularly important consideration for younger Indian patients undergoing THA.

DISCUSSION

Acetabular Size and the Implant Mismatch Problem

The mean acetabular transverse diameter of 45.8 mm in this study is significantly smaller than Caucasian values (53.1 mm; Rubin et al., 2006) and marginally smaller than East Asian series (46.5–47.2 mm). This 15% size differential represents a clinically meaningful discrepancy when applying Western-designed acetabular cups to Indian patients. Press-fit cups inserted into an undersized acetabulum require aggressive impaction, risking acetabular fracture, cup migration, and excessive peri-prosthetic bone stress. Conversely, cups selected conservatively may lack adequate press-fit, compromising primary stability.

The data from this study provide the foundation for a proposed Indian-standard acetabular cup size distribution: 44–52 mm cups should constitute the majority of surgical stock, with 54–58 mm cups reserved for larger male patients. This recommendation diverges substantially from the current size distribution in Western implant sets.

Elliptical Morphology — Challenge and 3D Printing Solution

The predominance of elliptical acetabular morphology (54.2%) in this study — versus the round morphology assumed by hemispherical press-fit cup design — is a central finding with significant practical implications. Standard hemispherical cups achieve their press-fit by displacing a defined volume of cancellous bone around their circumference as they are impacted. In an elliptical acetabulum, this contact is non-uniform, creating areas of excessive stress and gaps, increasing micromotion and risk of cup migration.

Three-dimensional printing directly addresses this limitation. Unlike conventional machined cups constrained to hemispherical geometry, 3D-printed cups can be manufactured in customised ellipsoidal or other non-circular cross-sections precisely matched to the patient's acetabular shape. This capability makes 3D printing particularly valuable for the Indian population, where elliptical morphology is prevalent.

Female Acetabular Characteristics and THA Planning

Females in this study exhibited significantly higher acetabular index (41.6° vs. 38.1° in males) and anteversion angle (19.5° vs. 17.6°). The higher AI in Indian women approximates the dysplastic threshold (45°) in a non-trivial proportion, suggesting heightened susceptibility to instability with standard cup placement protocols. The elevated anteversion, combined with the cultural prevalence of deep squatting activities, substantially increases the risk of anterior dislocation in female Indian THA patients.

These findings support the use of combined anteversion technique (targeting total anteversion of femoral + acetabular components between 25°–50°, per Widmer's formula) and patient-specific surgical cutting guides — readily fabricated by 3D printing — to ensure individually optimised cup orientation in Indian female patients.

3D Printing: Challenges in the Indian Healthcare Context

Despite its potential, widespread clinical adoption of 3D printing for THA in India faces several challenges:

- Cost: Patient-specific 3D-printed titanium cups cost approximately INR 1.5–4 lakhs per implant, compared to INR 40,000–1.2 lakhs for standard imported cups. Economies of scale and domestic manufacturing capacity are required to close this gap.
- Regulatory pathway: CDSCO classification of custom 3D-printed implants as Class C devices requires clinical evaluation data, hospital-level regulatory approval, and surgeon credentialing — bureaucratic barriers not faced by off-the-shelf implants.
- CT access and quality: The workflow requires high-quality thin-slice CT (≤ 0.5 mm), unavailable or inconsistently available at many district and rural hospitals where the burden of hip disease is high.
- Digital workflow expertise: Segmentation, CAD design, and quality verification require trained biomedical engineers — a nascent workforce in most Indian hospitals.
- Sterilisation and logistics: Sterilisation of custom implants requires ethylene oxide or gamma irradiation facilities, with turnaround times of 5–10 days, necessitating lead time in elective cases.

Mitigation strategies include: centralised 3D printing hubs at tertiary institutions providing cups to regional hospitals; telemedicine-based segmentation services; government subsidies for domestic implant manufacturers; and integration of 3D printing curricula into orthopaedic residency training programmes.

Future Directions

The convergence of population-specific morphometric databases, artificial intelligence-assisted CT segmentation, and high-throughput metal additive manufacturing offers a future where every THA in India is performed with an implant precisely sized and shaped to the individual patient's acetabular anatomy. Key research priorities include: (1) establishment of a pan-Indian morphometric database with ethnic and regional stratification; (2) development of AI-assisted automated segmentation and cup sizing algorithms trained on Indian CT data; (3) multi-centre RCTs comparing 3D-printed vs. conventional cups in the Indian population; and (4) health-economic analyses demonstrating cost-effectiveness over a 10-year horizon accounting for reduced revision rates.

Limitations

- Dry bone measurements exclude articular cartilage (estimated 2–4 mm), labral morphology, and capsular contributions to effective acetabular geometry — parameters relevant to functional cup sizing.
- Regional diversity of India's 1.4 billion population is incompletely represented by three collection sites, limiting inter-regional generalisability.
- Precise skeletal age could not be determined for individual specimens; age-stratified morphometric analysis was therefore not feasible.
- The 3D printing review component is narrative rather than a formal PRISMA-compliant systematic review; selection bias in included studies cannot be excluded.
- Male specimens predominated (65%), reflecting anatomy department collection demographics, potentially limiting female-specific normative precision.

CONCLUSION

This study presents the most comprehensive multi-parameter osteometric analysis of the acetabulum in adult Indian dry hip bones to date, encompassing 120 specimens and 11 morphometric parameters. The Indian acetabulum is characterised by smaller diameters, predominantly elliptical morphology, higher acetabular inclination in females, and moderately elevated anteversion — all parameters distinct from Western reference values.

These findings confirm the clinical imperative for population-specific implant sizing and

individualised cup positioning in THA for Indian patients. Three-dimensional printing technology provides a powerful and increasingly accessible solution to this challenge, enabling fabrication of anatomically optimised acetabular components with engineered porous ingrowth surfaces tailored to each patient's CT-derived morphology. The integration of Indian morphometric data with 3D printing workflows — from pre-operative physical models and surgical cutting guides to patient-specific custom cups — represents a paradigm shift towards precision orthopaedics in THA.
Wider adoption of this integrated approach, supported by investment in domestic manufacturing capacity, regulatory streamlining, and training of biomedical engineering personnel, has the potential to significantly improve THA outcomes in India and reduce the human and economic burden of revision surgery.

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Declaration of Competing Interests: None declared. | Funding: Institutional Research Grant [Ref. XX/YYYY]