Indian J. Applied & Pure Bio. Vol. 41(2), 1201-1210 (2026). **ISSN: 0970-2091**

Reconstructing Anatomy without Harm: The Role of 3D-Printed Bone Models in Inclusive Medical Education

[1]Nirav Patel and [2]Saurabh Verma

[1,2]Department of Rachana Sharir, Parul Institute of Ayurved, Parul University,
Vadodara - 391760 (India)
Corresponding Author - Dr. Saurabh Verma, P.G Scholar, Department of Rachana Sharir,
Parul Institute of Ayurved, Parul University, Vadodara, Gujarat, (India)

Abstract

Anatomical education has historically depended on cadaveric dissection as the cornerstone for teaching human structure; however, this approach is increasingly challenged by ethical concerns, high operational costs, biohazard risks, donor scarcity, and religious sensitivities. In particular, students adhering to non-violent philosophies such as *ahimsa* in Jainism may experience moral conflict when required to handle human remains, potentially limiting inclusive access to medical education. Three-dimensional (3D) bone printing, enabled by additive manufacturing technologies, offers a compelling alternative by producing accurate, durable, and customizable skeletal models derived from non-invasive medical imaging data. This article examines the complete workflow of classroom-oriented 3D bone printing, encompassing image acquisition, digital segmentation, computer-aided design, printing technologies, material selection, and post-processing. The educational, ethical, economic, and environmental implications of adopting 3D-printed bone models are critically analyzed. Evidence indicates that these models enhance spatial understanding, allow repetitive hands-on learning, enable visualization of rare pathologies, and support interdisciplinary STEM skill development, while significantly reducing reliance on cadavers. Although limitations remain in replicating biological variability and tactile realism, 3D-printed bones function effectively as a complementary teaching tool. Overall, 3D bone printing represents a transformative, ethically inclusive, and sustainable advancement in modern anatomy education with significant potential for widespread adoption.

Key words : 3D Printing; Anatomical Models; Bone Reconstruction; Medical Education; Bioethics; Jainism; Additive Manufacturing; STEM Education; Biomedical Materials.

---

[1]Associate Professor, [2]P.G. Scholar

The fundamental basis of the biological and medical sciences is anatomical knowledge. Cadaveric dissection has been the standard technique for teaching this knowledge for centuries. Although invaluable, this practice has many drawbacks, including high acquisition and preservation costs, strict storage regulations, a lack of donors, possible biohazard risks, and inherent specimen variability that can make teaching standard anatomy more difficult.[1]

There are significant ethical and religious issues that go beyond these pragmatic limitations. Mandatory contact with human cadavers can be extremely upsetting and contentious for students who follow religions that place a strong emphasis on nonviolence, the sanctity of the dead, or particular purity regulations. The concept of ahimsa, or non-harm, is fundamental to Jainism. The direct handling and dissection of a human body can be extremely unsettling for a devout Jain student, even though the use of cadavers for medical education is frequently contextualized. This could deter gifted people from pursuing careers in medicine or the life sciences.[2] In a similar vein, students from different cultural or religious backgrounds might object out of respect for the departed.

The emergence of additive manufacturing, commonly known as 3D printing, signifies a transformative shift in anatomical education, with 3D bone printing presenting a particularly advantageous approach. This technology facilitates the production of precise, physical, and patient-specific representations of skeletal anatomy, utilizing non-invasive medical imaging data such as CT or MRI scans.[3] These models possess the capacity for unlimited reproduction, global digital sharing, and manipulation devoid of ethical concerns. They establish a consistent, error-free benchmark for instructional purposes and can even simulate pathological states. This paper posits that 3D-printed bone models constitute a crucial advancement, broadening access to superior anatomical specimens while cultivating an inclusive educational setting that acknowledges diverse ethical and religious perspectives. The following sections will thoroughly examine the process, technological underpinnings, materials, and pedagogical implications of this innovative tool.

Aim and Objective :

Aim:

To evaluate the role of 3D bone printing as an ethical, educational, and practical alternative to cadaver-based teaching in anatomy classrooms.

Objectives :

1. To describe the complete workflow involved in creating 3D-printed bone models for educational use.
2. To assess the educational benefits of 3D-printed bones in enhancing spatial understanding and hands-on learning.
3. To analyze ethical and religious considerations, particularly in relation to non-violence principles such as *ahimsa*.
4. To identify the advantages, limitations, and future potential of 3D bone printing in anatomy education.

This article is a narrative review of published literature on the use of 3D bone printing in anatomical education. Relevant scientific articles, reviews, and educational reports were identified from standard academic sources focusing on additive manufacturing, anatomy teaching models, biomedical materials, and ethical considerations. Information was synthesized to describe commonly used technologies, materials, workflows, educational outcomes, and ethical implications, with particular attention to non-cadaveric teaching alternatives and religious perspectives such as Jainism. No experimental procedures or human/animal subjects were involved.

The Complete Process of Creating 3D-Printed Bone Models for the Classroom:

The creation of a classroom-ready 3D-printed bone model is a multi-stage process integrating digital imaging, computer-aided design (CAD), and additive manufacturing.

Step 1: Image Acquisition :

The process begins with medical imaging data. Computed Tomography (CT) scans are the gold standard for bone imaging due to their excellent contrast for hard tissues. DICOM (Digital Imaging and Communications in Medicine) files from a CT scanner provide the necessary cross-sectional data of the skeletal region of interest.[9] MRI data can be used but is more complex for bone segmentation. For educational purposes, databases of anonymized patient scans or scans of anatomical donors (with consent) are utilized.

Step 2: Segmentation and 3D Model Generation :

The DICOM files are imported into specialized segmentation software (*e.g.*, 3D Slicer, Mimics, OsiriX). Here, the crucial step of **segmentation** occurs. Using grayscale thresholds, the user differentiates bone (which appears bright/white due to high X-ray absorption) from surrounding softer tissues. This process isolates the desired bone structure. The software then generates a 3D surface mesh file, typically in STL (Stereolithography) or OBJ format, which defines the outer geometry of the model. This digital model can be cleaned, smoothed, and scaled as needed.

Step 3: Digital Preparation and Slicing :

The STL file is imported into printer-specific slicing software (*e.g.*, Ultimaker Cura, PrusaSlicer). This software digitally slices the 3D model into hundreds or thousands of thin horizontal layers (*e.g.*, 0.1-0.2 mm thick). It also generates the necessary support structures for overhanging features (like the scapular spine or femoral neck) and calculates the toolpath (G-code) that the printer will follow, layer by layer.[10]

Step 4: 3D Printing (Additive Manufacturing):

The G-code is sent to the 3D printer. The printer builds the model layer by layer using the chosen material and technology (detailed in sections 3 & 4).

Step 5: Post-Processing :

Once printing is complete, the model requires post-processing:

1. **Support Removal:** Any support structures are carefully removed using pliers or cutters.
2. **Cleaning:** Residual powder or support material is cleaned off (methods vary by

technology).

3. **Curing:** For resin-based prints, a final UV cure is required to achieve full mechanical strength.
4. **Finishing:** Models may be sanded, polished, or painted for enhanced anatomical detail or color-coding of structures.

The 3D Bone Printing Machine: Technologies for the Classroom :

Educational institutions primarily use two types of affordable, desktop-friendly 3D printing technologies for bone model production:

Fused Deposition Modeling (FDM) :

- **Principle:** A thermoplastic filament is fed through a heated extruder, melted, and deposited layer-by-layer onto a build platform.
- **Typical Classroom Printer:** Ultimaker S5, Prusa i3 MK3S+, Creality Ender 3.
- **Advantages for Education:** Low cost per print, wide material variety (PLA, ABS), robust and durable models, relatively easy operation and maintenance.
- **Disadvantages:** Layer lines visible (reduced accuracy), slower for high-detail models, may require significant post-processing for smooth surfaces.

Stereolithography (SLA) / Digital Light Processing (DLP) :

- **Principle:** A vat of liquid photopolymer resin is selectively cured by a UV laser (SLA) or a UV light projector (DLP), solidifying the resin layer by layer.
- **Typical Classroom Printer:** Formlabs Form 3, Anycubic Photon.
- **Advantages for Education:** Exceptionally high resolution and smooth surface finish, excellent for capturing fine anatomical details (*e.g.*, trabecular bone texture, tiny foramina).
- **Disadvantages:** Higher material cost, resin is messy and requires careful handling (skin irritation risk), models can be brittle, requires post-print UV curing and alcohol washing.

For advanced biomedical research, technologies like **Selective Laser Sintering (SLS)** or **Binder Jetting** are used to create models from nylon or composite powders, offering different mechanical properties but at a higher cost and machine footprint.[12]

Materials used and their Chemical properties :

The choice of material is critical and differs between educational models and clinical, implantable scaffolds.

Materials for Educational/Replica Models:

These materials prioritize cost, printability, safety, and tactile properties over biocompatibility.

1. *Polylactic Acid (PLA):*

   - **Chemical Property:** A biodegradable aliphatic polyester derived from renewable resources (corn starch, sugarcane). Its polymer chain is composed of repeating lactic acid units. It has a glass transition temperature (Tg) of ~55-60°C and a melting point of ~150-160°C.
   - **Educational Use:** The most popular choice. It is easy to print, odorless, rigid, and available in many colors. It is brittle

under impact but sufficiently strong for handling.

2. *Acrylonitrile Butadiene Styrene (ABS):*

- **Chemical Property:** A thermoplastic copolymer comprised of acrylonitrile, butadiene, and styrene monomers. It has a Tg of ~105°C. It is known for its toughness and impact resistance due to the polybutadiene rubber component.
- **Educational Use:** Creates more durable, slightly flexible models than PLA. Requires a heated print bed and good ventilation due to styrene fumes during printing.

3. *Photopolymer Resins (for SLA/DLP):*

- **Chemical Property:** These are mixtures of monomers (*e.g.*, acrylates, methacrylates) and oligomers that undergo free-radical polymerization when exposed to specific UV light wavelengths. A photoinitiator compound triggers the reaction.
- **Educational Use:** "Standard" or "Tough" resins produce hard, detailed models. They are thermosets (cannot be re-melted). "Flexible" or "Dental" resins mimic different tissue feels.

Materials for Implantable Bone Scaffolds (Research Context) :

These are bioactive and designed to degrade *in vivo* while supporting bone regeneration.

1. Bioceramics:

- **Hydroxyapatite (HA):** $Ca_{10}(PO_4)_6(OH)_2$. The natural mineral component of bone. Chemically similar, it promotes osteoconduction (bone growth along its surface). Brittle and difficult to print alone, often used in composites.
- **Tricalcium Phosphate (TCP):** $Ca_3(PO_4)_2$. More soluble than HA, degrades faster *in vivo*. Often blended with HA to tailor degradation rates.

2. *Biodegradable Polymers :*

- **Polycaprolactone (PCL):** A semi-crystalline polyester with a low melting point (~60°C) and slow degradation rate (years), suitable for long-term scaffolds.
- **PLA and its copolymers (PLGA) :** PLGA (Poly(lactic-co-glycolic acid)) degradation rate can be tuned by the lactic/glycolic acid ratio. Degradation products are metabolized.

3. *Metal Alloys:*

- **Titanium (Ti-6Al-4V) and Tantalum:** Used in powder bed fusion (SLM) printing for permanent, load-bearing implants. Excellent strength-to-weight ratio and biocompatibility.

Figure 1 SKULL BONE MODEL

Figure 2 HIP BONE MODEL

Figure 3 FEMUR BONE MODEL

Figure 4 SCAPULA BONE MODEL

A good balance between benefits and drawbacks was found in the evaluation of 3D-printed bone models in anatomy education. In terms of ethics, these models significantly lessen the use of human cadavers, addressing issues pertaining to consent and being consistent with non-violent ideals like ahimsa in Jain philosophy. From an accessibility perspective, digital models can be created on demand and disseminated worldwide, facilitating broader adoption in institutions with limited resources. Several studies show that 30–60% lower long-term costs are associated with 3D printing infrastructure than with cadaver procurement, preservation, and disposal, despite the high initial investment.

Through color-coding and modular

designs, 3D-printed bones facilitate repetitive practice, standardized anatomy, and the visualization of uncommon pathologies. In terms of education, students report better spatial comprehension and exam performance when compared to atlas-based learning alone. They do not, however, accurately reflect anatomical variation between individuals. The tactile feedback and micro-architecture of printed models are different from those of natural bone, but they are robust, reusable, and free of chemical preservatives.

Although it necessitates knowledge of digital design, customization enables scaling, sectioning, and patient-specific modeling, improving targeted learning and surgical simulation. These models are long-lasting, non-biohazardous, and simple to store logistically. Although energy consumption and plastic waste from unsuccessful prints are still issues, additive manufacturing using materials like PLA minimizes material waste. Although they cannot simulate bleeding or live tissue resistance, 3D-printed bones are useful for preoperative planning and osteotomy rehearsal in surgical training.

Table-1. Pros and Cons of 3D-Printed Bones in Anatomy Education

Aspect	**Pros (Advantages)**	**Cons (Disadvantages)**
Ethical & Religious	Eliminates need for cadavers; respects religious beliefs (*e.g.,* Jain *ahimsa*); no donor-related ethical concerns	May be perceived as less authentic or emotionally impactful than real human tissue
Accessibility & Cost	On-demand production; global sharing of digital files; lower long-term costs	High initial cost of printers, software, and training
Educational Value	Unlimited repetition; color-coded structures; replication of rare pathologies; standardized anatomy	Absence of natural anatomical variability
Handling & Durability	Robust; reusable; no chemical preservatives	Tactile properties differ from real bone; some materials are brittle
Customization	Digital scaling, sectioning, modular and interactive designs	Requires time and technical design skills
Logistics	No refrigeration or special storage; no infection risk; long shelf life	Requires space for printing and post-processing; ongoing maintenance
Environmental Impact	Use of biodegradable PLA; reduced material waste; minimal transport	Plastic waste from failed prints; energy use; resin disposal issues
Surgical Training	Useful for patient-specific planning and osteotomy practice	Cannot simulate bleeding, healing response, or live tissue resistance

These point discussion synthesize the key implications of integrating 3D bone printing into anatomical classrooms.

1. Fostering Ethical Inclusivity and Respect for Religious Sensibilities: This is arguably the most profound impact. By providing a high-fidelity, non-cadaveric alternative, 3D printing removes a major barrier for students like Jains, for whom *ahimsa* extends to all life, including the deceased.[4] It aligns education with the principle of minimizing harm, allowing these students to pursue anatomical knowledge without compromising core religious values. It similarly accommodates students from other faiths or personal ethical stances, creating a universally accessible learning environment.

2. Democratization of Anatomical Knowledge : Digital STL files of anatomical models can be shared freely online or through academic networks. This allows institutions in resource-limited settings, lacking access to cadaver labs, to download and print their own teaching collections. It levels the global playing field in anatomical education.[5]

3. Enhanced Spatial Understanding Through Haptics: While digital 3D models on screens are useful, the tactile, kinesthetic feedback from holding and rotating a physical 3D print significantly enhances spatial learning and memory retention.[6] Students can appreciate depth, curvature, and relationships between structures in a way that 2D atlases cannot provide.

4. Customization for Targeted Learning : Instructors are no longer limited to standard commercial models. They can print isolated bones, section them to reveal internal architecture (like the femoral neck trabeculae), magnify tiny structures (ossicles), or print common fracture patterns to teach surgical fixation. Learning becomes modular and objective-focused.

5. A Tool for Interdisciplinary Education: The process itself—from imaging to segmentation to printing—teaches valuable skills in biomedical engineering, computer science, and design thinking. Anatomy classrooms become hubs for STEM integration, preparing students for the technologically advanced future of medicine.

6. Environmental Sustainability Considerations: Using bio-based plastics like PLA reduces reliance on fossil-fuel-derived materials and formaldehyde-based preservation.[7] While 3D printing has an energy footprint, its on-demand, local production model eliminates the carbon emissions associated with shipping heavy, manufactured models from centralized factories. Responsible waste management of support materials and resins is, however, essential.[11]

7. Economic Viability and Long-Term Cost Savings : Despite the upfront costs, the long-term economics are favorable. A single printer can produce hundreds of models over its lifetime for the cost of material (often a few dollars per model). This contrasts with the recurring, high costs of cadaver procurement, embalming, ventilation, and specialized lab facilities.

8. Challenges in Simulating Biological Complexity : A significant limitation is the inability to replicate the complete biological environment—the feel of cutting through cortical vs. cancellous bone, the presence of periosteum, marrow, and associated soft tissues. Therefore, 3D prints are best viewed as a powerful **complement** to, not a full **replacement** for, a multimodal curriculum that may also include prosection videos, virtual reality, and, where acceptable, cadaveric study.[13]

9. Quality Assurance and Anatomical Accuracy: The accuracy of the final model is contingent on every step: scan resolution, segmentation skill, printer calibration, and material choice. Educators must validate models against trusted anatomical sources to ensure they are teaching correct anatomy. "Garbage in, garbage out" applies fully here.

10. Future Trajectory : Towards Bioprinting and Dynamic Models : The logical progression is towards multi-material printing that combines rigid "bone" with flexible "ligament" materials, and ultimately, the incorporation of live cells (bioprinting) for advanced tissue engineering studies.[8] For now, even simple single-material bone prints represent a massive leap forward in accessible, ethical education.

3D bone printing has unequivocally introduced a new dimension into the landscape of anatomical reconstruction for the classroom. It successfully addresses a triad of enduring challenges: ethical and religious barriers, logistical and economic constraints, and the need for customizable, precise teaching tools. By providing a physically tactile, accurate, and reproducible alternative to cadaveric specimens, it empowers all students—regardless of personal or religious background—to engage fully with the complex architecture of the human skeleton. The technology champions an inclusive educational philosophy while simultaneously imparting crucial 21st-century digital skills. While it does not entirely replicate the multisensory experience of human tissue, its advantages in accessibility, ethics, and versatility make it an indispensable component of modern anatomical science pedagogy. As materials and printers continue to evolve, their role will only expand, solidifying 3D printing not as a novelty, but as a cornerstone of responsible and innovative anatomical education.

References :

1. AbouHashem Y, M Dayal, S Savanah, and G. Štrkalj (2015). The application of 3D printing in anatomy education. Med Educ Online. 20: 29847. doi:10.3402/meo.v20.29847.
2. Chytas D, EO Johnson, M Piagkou, A Mazarakis, GC Babis, and E Chronopoulos *et al.* (2022). Surg Radiol Anat. *44*(9): 1217-29. doi:10.1007/s00276-022-03008-4.
3. Garg K. (2018). *J Med Ethics Hist Med. 11:* 14.
4. Hoang D, D Perrault, M Stevanovic, and A. Ghiassi (2016). *Ann Transl Med. 4*(23): 456. doi:10.21037/atm.2016.12.18.
5. Ibrahim D, TL Broilo, C Heitz, MG de Oliveira, HW de Oliveira, and SM Nobre, *et al.* (2009). *J Craniomaxillofac Surg. 37*(3): 167-73. doi:10.1016/j.jcms.2008.10.008.
6. Javaid M, and A. Haleem (2020). *J Clin Orthop Trauma. 11*(Suppl 5): S799-S806. doi:10.1016/j.jcot.2020.07.012.
7. Li J, M Chen, X Fan, and H. Zhou (2016).

J Transl Med. 14(1): 271. doi:10.1186/s12967-016-1028-0.

8. McMenamin PG, MR Quayle, CR McHenry, and JW. Adams (2014). *Anat Sci Educ. 7*(6): 479-86. doi:10.1002/ase.1475.
9. Rengier F, A Mehndiratta, H von Tengg-Kobligk, CM Zechmann, R Unterhinninghofen, and HU Kauczor, *et al*. (2010). *Int J Comput Assist Radiol Surg. 5*(4): 335-41. doi:10.1007/s11548-010-0476-x.
10. Tack P, J Victor, P Gemmel, and L. Annemans (2016). *Biomed Eng Online. 15*(1): 115. doi:10.1186/s12938-016-0236-4.
11. Vaz VM, and L. Kumar (2021). *AAPS Pharm Sci Tech. 22*(1): 49. doi: 10.1208/s12249-020-01905-8.
12. Wu C, Y Luo, G Cuniberti, Y Xiao, and M. Gelinsky (2011). *Acta Biomater. 7*(6): 2644-50. doi:10.1016/j.actbio.2011.03.009.
13. Yoo DJ. (2014). *Int J Precis Eng Manuf. 15*(10): 2205-17. doi:10.1007/s12541-014-0583-7.