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Development of a Patient-Specific Plate for Hoffa Fracture: CT-Based Segmentation and Additive Manufacturing Workflow

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1.ABSTRACT:

Hoffa fractures coronal fractures of the femoral condyle present a significant surgical challenge due to their intra-articular nature and anatomical complexity. Traditional fixation methods using generic implants often result in suboptimal fit, prolonged surgical time, and increased risk of malalignment. This study presents a complete digital workflow for the design, prototyping, and evaluation of a patient-specific implant (PSI) for Hoffa fractures using computed tomography (CT) data and additive manufacturing. The pipeline begins with segmentation of knee joint anatomy from DICOM-format CT scans using 3D Slicer, followed by conversion into STL models for mesh processing. Eight cases were evaluated, with one representative model selected for PSI design using Autodesk Meshmixer. The fracture surface was isolated, and a custom implant was designed to conform precisely to the patient's distal femur geometry. Screw placement and structural reinforcements were incorporated based on orthopedic fixation principles. The PSI and bone model were prototyped using fused deposition modeling (FDM) for validation. The 3D-printed implant demonstrated accurate anatomical fit and alignment, confirmed through visual inspection and feedback from an orthopedic surgeon. This workflow demonstrates a cost-effective and reproducible method for personalized orthopedic implant fabrication, with potential future applications in metal additive manufacturing using biocompatible materials such as Ti-6Al-4V.

KEYWORDS

applications, manufacturing, segmentation, deposition

2.INTRODUCTION:

Additive manufacturing has emerged as a transformative technology in orthopedic surgery, offering patient-specific solutions for preoperative planning and custom implant fabrication. As the field of personalized medicine evolves, 3D printing plays a pivotal role in translating radiological data into accurate anatomical models and customized implants that conform precisely to individual bone geometry. Patient-specific implants (PSIs) enhance surgical accuracy, particularly in anatomically complex regions such as the pelvis, spine, and distal femur, thereby reducing intraoperative decision-making time and improving outcomes [1].

To facilitate widespread clinical adoption, a structured approach for integrating 3D printing into orthopedic practice has been proposed, including guidelines for imaging, segmentation, model generation, and collaboration between surgeons and engineers [2]. This interdisciplinary workflow supports applications in trauma, deformity correction, and arthroplasty.

In the context of intra-articular injuries like Hoffa fractures—coronal fractures of the femoral condyle—standard fixation hardware may not match the joint surface geometry, increasing the risk of malreduction. 3D-printed anatomical models have enabled precise surgical planning and implant placement in complex Hoffa fracture nonunion cases [6].

Segmentation accuracy is foundational to PSI development. A level-set method for rapid cortical bone segmentation has been shown to be reliable in craniofacial workflows [3]. Open-source platforms like 3D Slicer, commonly used for DICOM processing and segmentation, offer accessibility and reproducibility in clinical settings.

Once segmentation is completed, mesh processing and design refinement are crucial. Intuitive mesh-editing tools have been used to develop patient-specific knee implants, showing how user-friendly platforms can enhance orthopedic customization [5]. Similarly, a complete digital workflow for surgical simulator models has demonstrated potential for extension to implant prototyping [4].

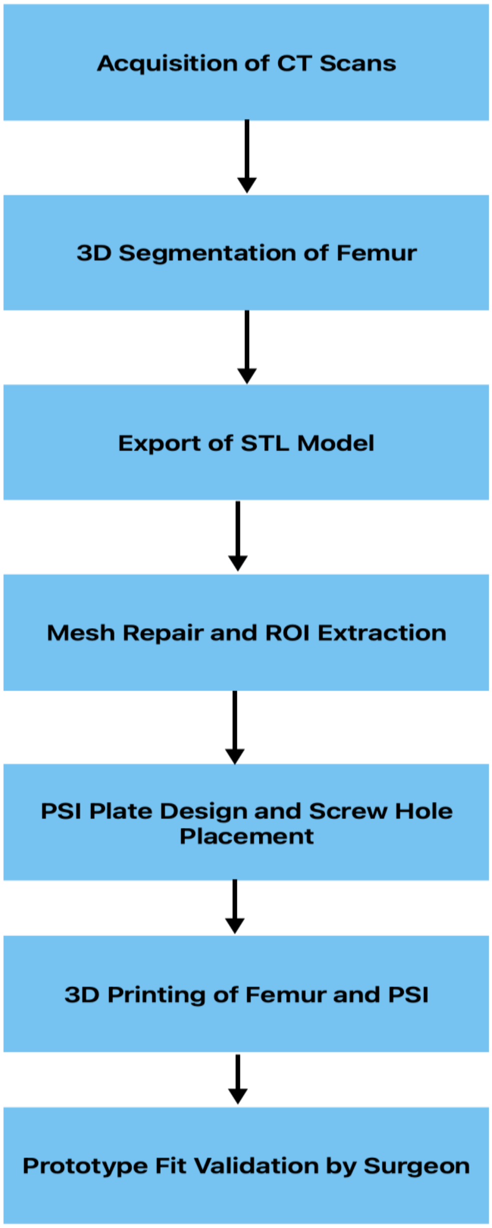
Material selection and manufacturing technique determine implant performance. Titanium alloy (Ti-6Al-4V) is the material of choice for orthopedic PSIs due to its strength and biocompatibility. Electron Beam Melting (EBM) has been used to fabricate Ti-6Al-4V implants with controlled microstructure and high mechanical integrity [7].

Patient-specific implant strategies are expected to grow in orthopedic trauma, particularly where conventional implants fail to address unique anatomical variations. Custom orthopaedic implants have been shown to improve surgical outcomes, reduce operating time, and enable minimally invasive procedures [8]. Additionally, embedding metadata into PSI design files has been proposed as a method for regulatory traceability and workflow optimization [9].

Building upon these developments, this study presents a complete digital-to-physical workflow for designing, prototyping, and validating a patient-specific implant for a lateral Hoffa fracture. The methodology integrates CT-based segmentation, mesh repair, CAD modeling, and FDM prototyping to create an anatomically conforming plate ready for transition to metal additive manufacturing.

3.METHODOLOGY:

The methodology followed in this study outlines a structured pipeline for developing a patient-specific implant (PSI) for Hoffa fracture fixation using medical imaging data, segmentation tools, mesh processing, and additive manufacturing. The approach includes the following stages: acquisition and segmentation of CT data, STL model generation, region of interest (ROI) isolation, PSI design, and 3D printing for validation.



3.1 Data Acquisition and Segmentation :

Computed Tomography (CT) data of the knee joint, acquired in standard DICOM (Digital Imaging and Communications in Medicine) format, was processed using 3D Slicer, an open-source medical image computing platform. The workflow consisted of multiple stages aimed at converting volumetric CT data into 3D-printable STL models. Initially, the DICOM files were imported into 3D Slicer, and the datasets were reviewed in axial, sagittal, and coronal planes to confirm anatomical orientation and image quality.

Bone segmentation was performed using the Segment Editor module. A new segment was created, and thresholding was applied using an appropriate Hounsfield Unit (HU) range to isolate cortical and trabecular bone structures. The segmented volume was then refined through tools such as smoothing to reduce surface noise and island removal to eliminate small, disconnected components. Upon completion, the segmented anatomy was converted into a closed 3D surface and exported in STL (Stereolithography) format.

A total of eight patient cases were processed using this pipeline. One representative case was selected for further implant design and validation through Fused Deposition Modeling (FDM)-based 3D printing. The complete dataset characteristics, including imaging dimensions, slice spacing, and patient demographics, are summarized in table 1.

Table 1: Summary of Patient CT Data Used for STL Model Generation

S.No	Image Dimensions	Image Count	Image Spacing (mm)	DOB/Gender
1	512X512	320	0.4X0.4X0.7	1954/F
2	512X512	330	0.4X0.4X0.7	1967/M
3	512X512	283	0.3X0.3X0.7	1968/F
4	512X512	368	0.4X0.4X0.7	1953/M
5	512X512	336	0.4X0.4X0.7	1954/F
6	512X512	368	0.4X0.4X0.7	1958/F
7	512X512	1192	0.9X0.9X1	1991/M
8	512X512	333	0.4X0.4X0.7	1953/F

3.2 Steps for DICOM to STL Conversion Using 3D Slicer:

The transformation of CT imaging data into 3D-printable models was carried out through a structured segmentation and export pipeline within 3D Slicer. The process consisted of the following sequential steps:

- **DICOM Import:** CT scan data of the knee joint, stored in DICOM format, was imported using the DICOM module in 3D Slicer. This facilitated the loading of volumetric image series with metadata intact.
- **Multiplanar Review:** The imported images were reviewed in axial, sagittal, and coronal views to assess anatomical completeness and confirm proper orientation of the dataset.
- **Bone Segmentation:** A new segment was initialized within the Segment Editor module. The Threshold tool was applied to isolate osseous tissue by selecting a Hounsfield Unit (HU) range typically between 150 and 3000, effectively distinguishing cortical and trabecular bone.
- **SegmentationRefinement:**
  Post-threshold refinement was performed using:
  - Smoothing to eliminate voxel-based surface irregularities,
  - Islands to remove disconnected fragments and noise, and
  - Scissors for manual exclusion of irrelevant regions.
- **3D Model Generation:** The refined segmentation was converted into a closed 3D surface using the Export to Models function, resulting in a high-fidelity anatomical mesh.
- **STL Export:** The finalized surface model was exported in STL format, making it compatible for downstream use in implant design and additive manufacturing workflows.

3.3 Benchmarking Against Conventional Orthopedic Fixation Devices:

Before designing the patient-specific implant, standard orthopedic fixation devices are reviewed for comparison. A conventional titanium plate with screws is studied to understand design standards for strength, hole placement, and fixation techniques.

Fig 1: Conventional Orthopedic Titanium Plate with Screws

3.4 Importing and Preprocessing the STL in Meshmixer for Design of PSI

The STL file generated from CT segmentation was imported into **Autodesk Meshmixer**, a mesh editing software widely used for anatomical modeling and implant design. A series of preprocessing steps were carried out to ensure the surface geometry was clean, accurate, and suitable for downstream processing:

- **Mesh Inspection:** The model was examined using Meshmixer's Inspector tool to identify and highlight surface anomalies, including holes, non-manifold edges, and disconnected components.
- **Mesh Repair:** Both automatic and manual repair operations were applied to close surface gaps, remove topological artifacts, and restore manifold geometry, ensuring structural integrity.
- **Solidification:** The Make Solid function was used to convert fragmented or thin-walled surfaces into watertight, printable solid bodies. This step was essential to prepare the model for implant design and fabrication.

Prior to this stage, medical imaging data such as CT or MRI scans were processed using segmentation software to reconstruct the 3D anatomical model of the knee joint. The resulting STL file, representing the bony and cartilaginous geometry, served as the foundation for patient-specific implant development. High geometric fidelity at this stage is critical to ensure accurate anatomical conformity of the final implant.

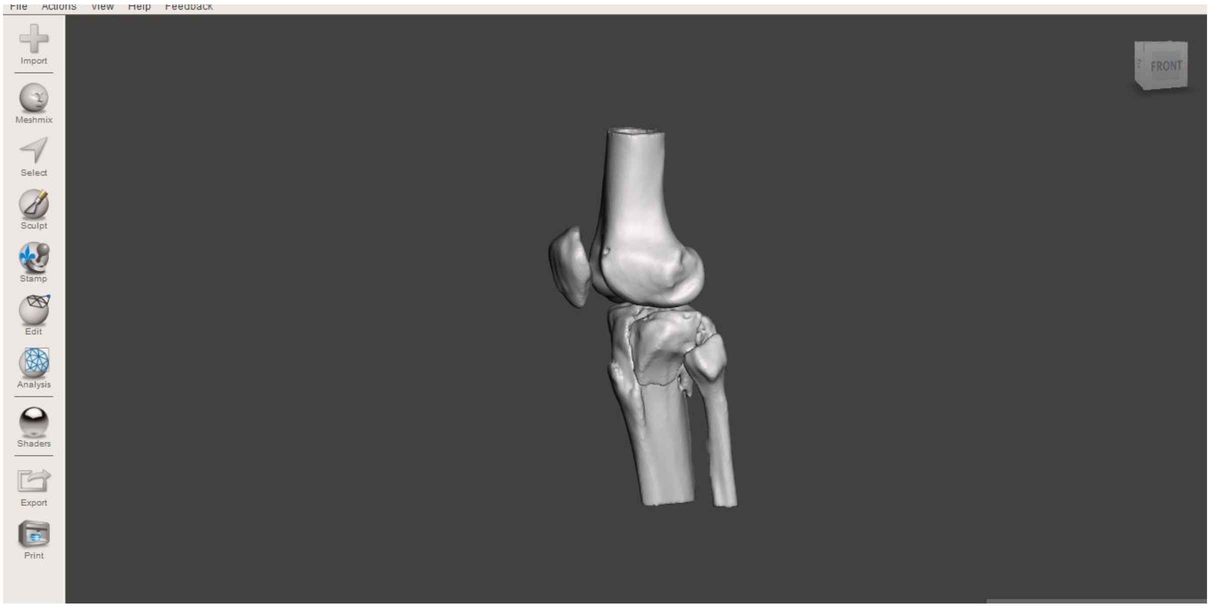


Fig 2: Meshmixer view of segmented femur STL model

Fig 3 : 3D Model of Distal Femur in Meshmixer

Fig 4 : 3D printed Model of Distal Femur

3.5. Identification and Selection of Region of Interest (ROI):

The region corresponding to the fracture site was identified based on anatomical landmarks visible in the segmented STL model of the distal femur. Using Meshmixer, the following steps were performed to accurately define the Region of Interest (ROI):

- **Surface Selection:** Interactive selection tools were used to highlight the fracture zone on the femoral condyle, focusing specifically on the coronal plane defect characteristic of a Hoffa fracture.
- **Boundary Refinement:** The initial selection was refined by adjusting edges and contours to ensure precise demarcation of the area requiring reconstruction, while avoiding overextension into healthy bone regions.
- **Preservation of Anatomy:** Care was taken to preserve the natural curvature and topography of the bone surface, ensuring that the eventual implant would conform closely to patient-specific anatomical features for optimal mechanical stability and surgical fit.

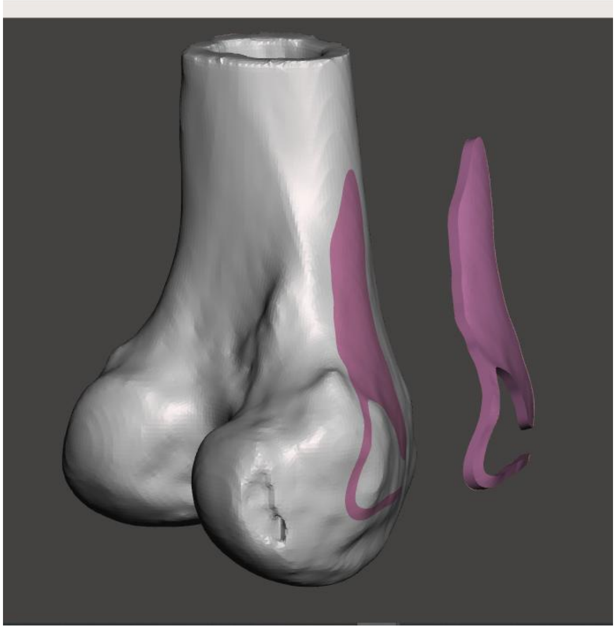


Fig 5: Surface Extraction from Region of Interest (Top View)

3.6. Surface Extraction and Preparation:

Following the selection of the Region of Interest (ROI), the corresponding surface geometry was extracted and processed as an independent mesh patch for implant design. The following steps were undertaken to ensure geometric accuracy and printability:

- **Mesh Extraction:** The defined ROI was isolated and extracted as a separate surface mesh, preserving its anatomical curvature and spatial orientation relative to the femur.
- **Surface Refinement:** Smoothing algorithms were applied to eliminate irregularities and sharp discontinuities, thereby improving surface continuity and ensuring a precise implant–bone interface.
- **Watertightness Verification:** The extracted mesh was evaluated for watertightness to confirm the absence of holes, non-manifold edges, or other defects that could compromise manufacturability or biomechanical stability.

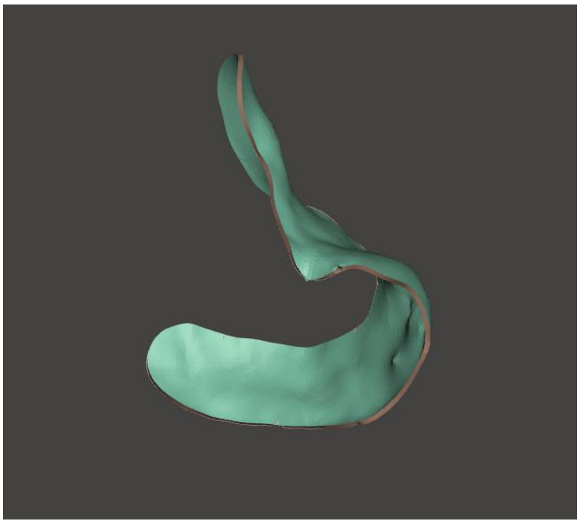


Fig 6: Extracted Fracture Surface Aligned with Femur Anatomy

3.7. Design of Patient-Specific Implant (PSI Plate)

The patient-specific implant (PSI) plate was designed directly within Autodesk Meshmixer, with the option for export to advanced CAD software if further refinement was required. The design process was guided by biomechanical and anatomical considerations to ensure optimal fixation and load distribution. Key steps included:

- **Anatomical Conformity:** The implant was sculpted to conform precisely to the previously extracted fracture surface, ensuring a flush interface with the femoral condyle and eliminating the risk of gaps or misalignment.
- **Structural Optimization:** The plate's thickness and curvature were tailored to provide sufficient biomechanical strength while maintaining anatomical compatibility. Design parameters were adjusted to balance rigidity and flexibility under physiological loads.
- **Geometric Coverage:** The plate was extended beyond the immediate boundaries of the fracture zone to enhance mechanical stability. Care was taken to minimize unnecessary bulk and avoid interference with adjacent anatomical structures.

Fig 7: Final PSI Plate Design with Screw Holes in Meshmixer.

3.8. Screw Hole Design and Fixation Planning:

To facilitate stable fixation, the patient-specific implant was designed to incorporate strategically positioned screw holes. The design process accounted for anatomical constraints, mechanical loading, and surgical feasibility. The following design considerations were applied:

- **Screw Hole Placement:** The number and locations of screw holes were optimized based on the fracture geometry, anticipated load distribution, and available bone stock. Placement was guided by orthopedic fixation principles to ensure secure anchorage without compromising joint function.
- **Dimensional Specification:** Each hole was dimensioned to accommodate standard orthopedic screws, typically in the 3.5–4.5 mm range. Countersinks were integrated into the design to allow screw heads to sit flush with or below the plate surface, minimizing soft tissue irritation post-surgery.
- **Structural Validation:** The final configuration was reviewed to ensure that screw placement did not weaken the implant structure or introduce stress concentrators. The integrity of the plate was preserved to withstand physiological loads while maintaining surgical accessibility.

3.9. Prototyping Using Additive Manufacturing

The PSI plate and femur model were 3D printed using polymer-based additive manufacturing. The printed model was used for physical validation of the digital design.

Fig 8: ELEGOO Neptune 4 Max 3D Printer

Table 2: Machine Specifications of ELEGOO Neptune 4 Max 3D Printer.

Product Model	Neptune 4
Build Volume	225 x 225 x 265 mm³
Filament Compatibility	PLA / TPU / PETG / ABS / ASA / Nylon
Printing Technology	FDM (Fused Deposition Modeling)
Printing Platform Size (Pei Area)	235 x 235 mm²
Maximum Size For Machine Activity/Mm	475 x 550 x 735 (Including Rack & Tray)

File Format	STL, OBJ
Max. Nozzle Temperature	300 °C
Max Speed Of Tool Head	500 mm/s

Fig 9: 3D Printed Femur and PSI Implant Validation Prototype

The assembled 3D-printed bone model and PSI plate were carefully examined for geometric conformity and anatomical fit. The implant demonstrated consistent surface contact with the femoral condyle and maintained alignment with the pre-defined fixation points.

Minor adjustments were identified during this evaluation, primarily aimed at improving surgical accessibility and manufacturing precision. These refinements were documented and incorporated into the final digital model

4.RESULT AND DISCUSSION:

4.1 CT Segmentation and Model Reconstruction

All **eight CT datasets** were successfully segmented using 3D Slicer to generate 3D femur models. In each case, the **Hoffa fracture line** was clearly identifiable. The case selected for implant design exhibited a **Letenneur Type III lateral condyle fracture**, suitable for demonstrating the full workflow.

The segmented femur STL consisted of approximately **120,000 triangular facets**, indicating a high-resolution reconstruction. The extracted condylar region, isolated for implant interface, contained **10,000 triangles**. After Meshmixer's **"Make Solid"** operation and post-processing, the final implant plate model contained **25,000 triangles**.

4.2 Geometric Analysis of Implant Fit

Deviation analysis between the PSI plate and the femoral condyle surface confirmed **sub-millimeter conformity**, with a maximum deviation of **less than 0.5 mm** across the contact interface. This confirmed that the implant geometry closely matched the anatomical surface derived from CT data.

4.3 3D Printing and Physical Verification

The femur model and implant were fabricated using **FDM 3D printing** at a **1:1 scale**. The FDM printer used was an **ELEGOO Neptune 4 Max**, which allowed printing of fine anatomical detail using **PLA**

filament at **0.2 mm layer height**. The printed model captured the distal femur's morphology, including the Hoffa fracture plane.

Visual comparison between the printed model and CT slices revealed **1–2 voxel overlap**, within the expected tolerance range of the printer's resolution. No gaps were observed at the **bone–implant interface** during assembly.

4.4 Screw Trajectory and Mechanical Validation

All pre-planned screw trajectories were confirmed to be feasible on the 3D-printed model. **Drill sleeves** inserted into the printed screw holes passed through without collision, verifying alignment. The **countersunk screw heads** rested flush or below the bone surface, ensuring soft-tissue clearance and implant stability.

4.5 Clinical Evaluation and Design Approval

The prototype assembly was evaluated by a surgeon and the implant was confirmed to:

- Fully cover the fracture zone,
- Match the condylar curvature,
- Require **only minor refinements**, such as smoothing of sharp edges.

Based on this assessment, no major revisions were needed, and the final design was deemed ready for **metal additive manufacturing**.

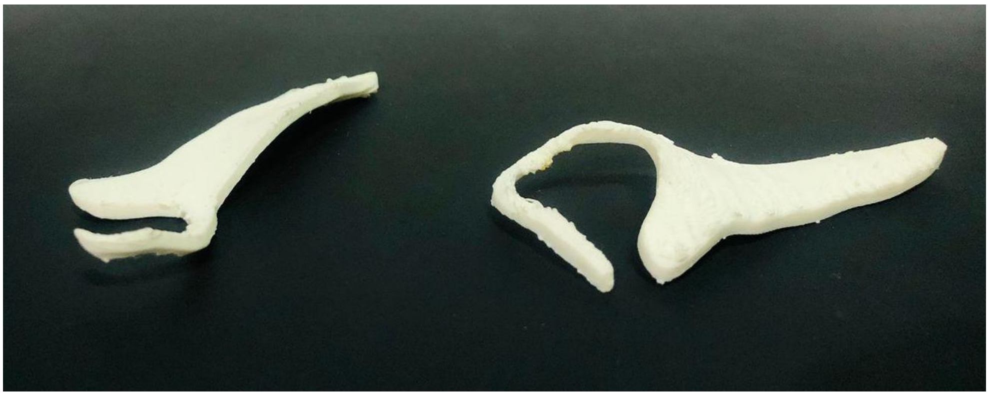


Fig 10: Final Design Refinement

Future Scope:

Metal Additive Manufacturing of the Final Implant

The validated PSI design is prepared for metal 3D printing using Selective Laser Melting (SLM) or Electron Beam Melting (EBM). Steps include:

- Optimizing build orientation and support structures to minimize distortion.
- Printing using biocompatible titanium alloy (e.g., Ti-6Al-4V).
- Post-processing: removal of supports, surface finishing, and heat treatment for stress relief and mechanical property enhancement.

5. CONCLUSION

This study presents a comprehensive patient-specific workflow for the design, prototyping, and evaluation of a custom fixation plate for lateral Hoffa fractures. The process began with CT-based segmentation using 3D Slicer, followed by mesh processing and implant design in Autodesk Meshmixer, resulting in an implant geometry tailored precisely to the patient's distal femoral anatomy.

Prototyping using Fused Deposition Modeling (FDM) enabled physical validation of implant fit, alignment, and coverage. Surgeon-led evaluation confirmed the anatomical conformity and mechanical viability of the design. The ability to iterate rapidly using low-cost polymer models significantly improved the accuracy and readiness of the final implant.

With the digital model now validated, the workflow is well-positioned for translation to metal additive manufacturing using Selective Laser Melting (SLM) or Electron Beam Melting (EBM) in Ti-6Al-4V, a clinically accepted biocompatible alloy. The proposed approach demonstrates the feasibility of using open-source tools and in-house 3D printing to develop personalized orthopedic implants, offering potential improvements in surgical precision, implant fit, and overall patient outcomes in orthopedic trauma care.

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ANNEXURE

List of Cases considered for Understanding the autonomy to create PSI for Hoffa Fracture.

S.No	Image Dimensions	Image Count	Image Spacing (mm)	DOB/Gender
1	512X512	320	0.4X0.4X0.7	1954/F
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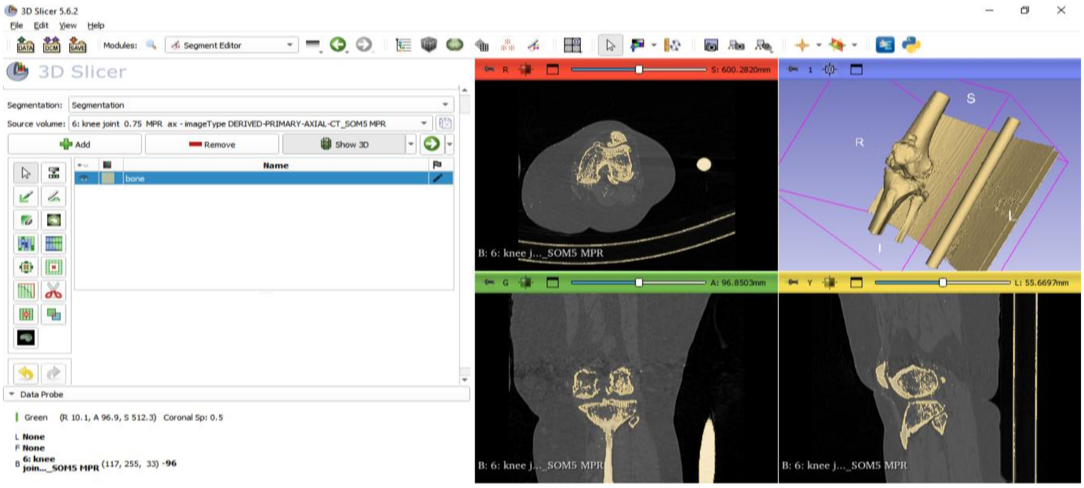
4	512X512	368	0.4X0.4X0.7	1953/M
5	512X512	336	0.4X0.4X0.7	1954/F
6	512X512	368	0.4X0.4X0.7	1958/F
7	512X512	1192	0.9X0.9X1	1991/M
8	512X512	333	0.4X0.4X0.7	1953/F



Segmentation: Segmentation

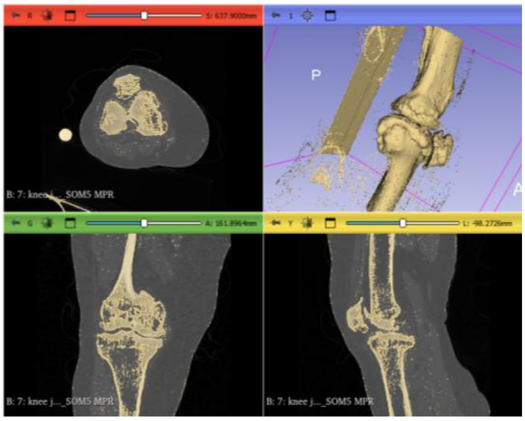
Source volume: 6: knee joint 0.75 MPR ax - imageType DERIVED-PRIMARY-AXIAL-CT_SOM5 MPR

bone

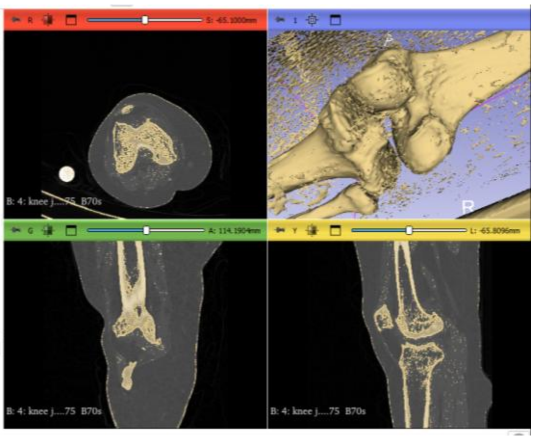
Green (R 10.1, A 96.9, S 512.3) Coronal Sp: 0.5

L None
F None
B 6: knee join..._SOM5 MPR (117, 255, 33) -96

CASE 1 Knee Joint



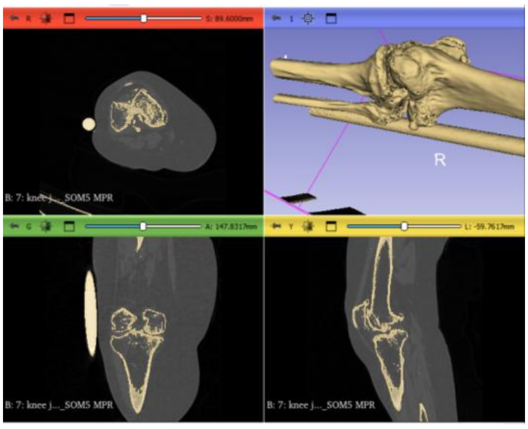
CASE 2 Knee Joint



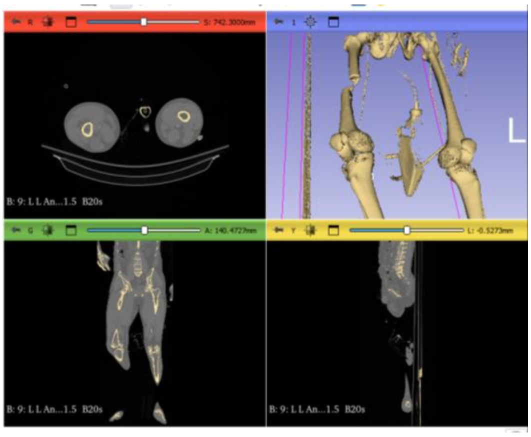
CASE 3 Knee Joint

CASE 4 Knee Joint

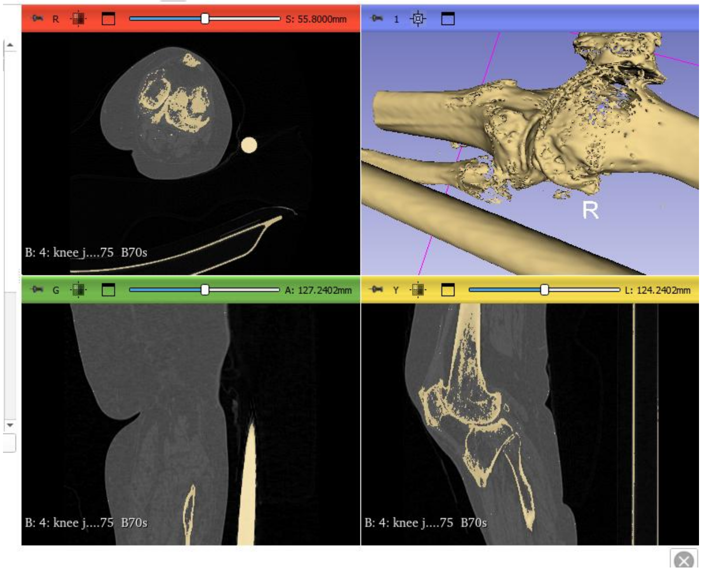
CASE 5 Knee Joint



CASE 6 Knee Joint



CASE 7 Knee Joint



CASE 8 Knee Joint.