A Parametric Modeling and 3D Printing Workflow for Patient-Specific Orthopedic Forearm Casts

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1. ABSTRACT

Traditional orthopaedic casts hold fractures but have drawbacks like discomfort, poor ventilation, weight, and non-recyclability. Personalized solutions are increasingly important in orthopaedics, prosthetics, and biomechanics, but often rely on expensive scanners or advanced CAD skills. This study offers an accessible method to create customized 3D hand models using basic measurements and 3D printing for forearm casts. Using key anthropometric data like palm width, finger lengths, and forearm circumferences, a parametric model was developed in SolidWorks supporting easy adjustments. The hand model was built in parts with measurements inputted automatically without scanning. The method enables efficient, accurate personalized hand models for medical, robotic, prosthetic, and educational uses. The cast, designed using Autodesk Meshmixer over a forearm model with perforations for breathability and rigidity, was printed with PLA on a Prusa i3 MK3S+. Tensile tests on PLA samples showed ultimate strengths of 0.4 kN and 63 N, respectively, on cylindrical and linear samples made using PLA material, confirming material suitability. A lightweight, comfortable, well-ventilated prototype weighing around 140 g cost about Rs1000. This research proves personalized orthopaedic casts can be effectively made with mesh-based digital modelling and 3D printing. Future work will explore new materials, adjustable fastenings, and clinical validation.

2. INTRODUCTION

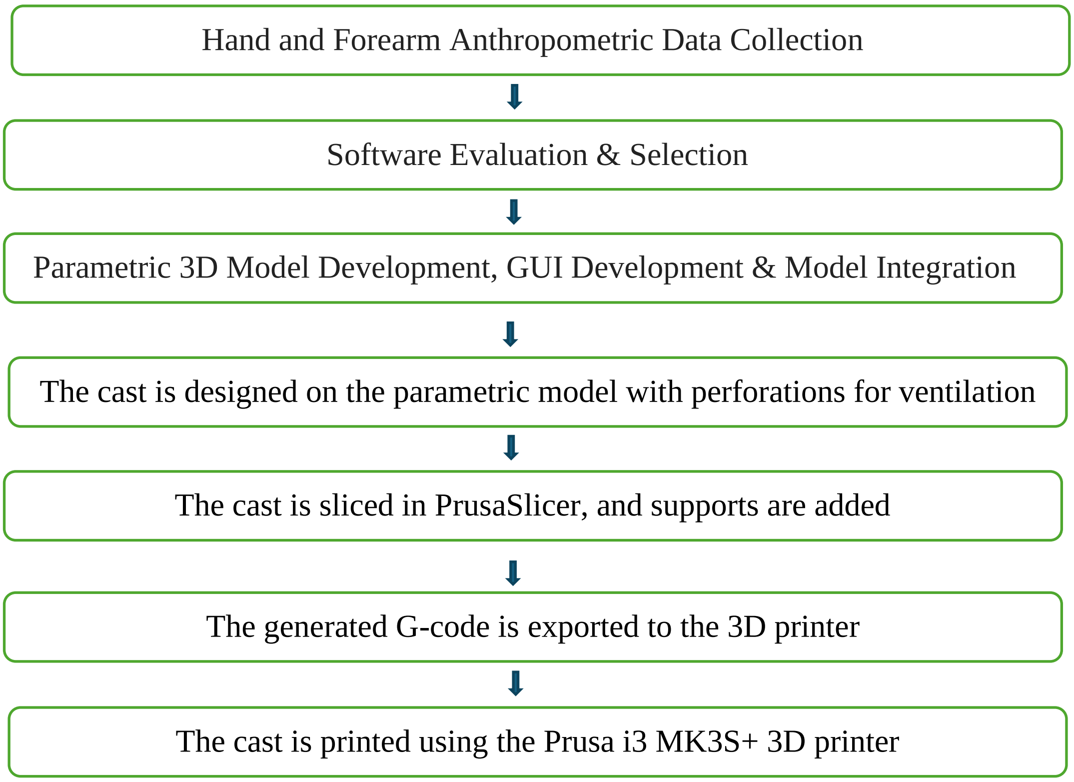
Most animals have a skeletal framework of bones that support and protect internal organs. Humans have about 206 bones connected by joints, allowing movement and protecting organs, but fractures can occur from impact, stress, or conditions like osteoporosis. Fractures require medical treatment for realignment and healing, using methods like plaster casts or surgery with metal implants. Treatment choice depends on fracture type, patient age, location, and health. Traditional orthopedic casts made of plaster or fiberglass are bulky, heavy, and uncomfortable, with long drying times, skin issues, and non-recyclability. Researchers seek better alternatives.

This research develops a parametric human arm model and creates a 3D-printed orthopedic forearm cast to improve patient comfort, usability, and fit. Traditional 3D modeling often relies on expensive 3D scanners or advanced CAD skills, making it costly, time-consuming, and less accessible in low-resource settings. This study develops an automated system for creating customizable 3D models of the human hand and forearm using limited anthropometric measurements. It involves analyzing data to identify key measurements and anatomical features for parametric modeling, evaluating CAD platforms, and creating a modular hand model in SolidWorks. A GUI was also developed for users to input measurements and generate STL models for 3D printing or simulation

Using this parametric model, a 3D-printed forearm cast was created with CAD, biocompatible materials like PLA, and additive manufacturing on a Prusa 3D printer. The research covers designing a parametric human arm model, creating the forearm cast, and manufacturing. It shows how modern technology can transform orthopedic rehabilitation.

3. METHODOLOGY

Phase 1 develops a patient-specific 3D hand model via a user-friendly interface for anthropometric data; Phase 2 uses this model to design a lightweight, breathable, functional 3D-printed cast that immobilizes fractures and enhances wearability and hygiene over traditional plaster casts.



Phase 1

The methodology included stages like identifying anthropometric parameters, evaluating design software, developing a 3D hand model, assembling anatomical parts, integrating geometric and numerical data, and designing a simple GUI.

3.1 Anthropometric Data Collection

Secondary anthropometric data from published literature ensured anatomical accuracy in the 3D hand model. Rostamzadeh et al. [1], analyzing 2,637 participants aged 7–18, provided key measurements like hand length, palm width, finger lengths, and forearm circumferences, ensuring reliability with standard instruments. Additionally, the study "3D Scanning of the Forearm for Orthosis and HMI Applications" [2] guided forearm modeling by introducing elliptical cross-sectional profiles suitable for parametric model generation.

Based on these sources, the following anthropometric parameters were selected for implementation:

- Palm length and depth
- Thumb and metacarpal breadths
- Finger lengths for digits one to five
- Finger circumferences at proximal and distal regions
- Forearm length and circumferences at 0%, 25%, 50%, 75%, and 100% of forearm length

These parameters enabled scalable, patient-specific adjustment while maintaining anatomical consistency.

3.2 Evaluation and Selection of 3D Design Software

Several 3D modeling platforms, OpenSCAD, Blender, Fusion 360, and SolidWorks—were evaluated for developing parametric, customizable hand models. Criteria included parametric control, organic geometry support, STL compatibility, ease of use, and learning curve. OpenSCAD was initially considered but was unsuitable for organic shapes. Blender's sculpting was effective for natural forms, but imported STL files couldn't be parametrically modified, limiting patient-specific modeling. Fusion 360 provided strong parametric control and dynamic updates using parameter-driven sketches and features like extrude, loft, and fillet. However, parameter updates failed after combining multiple bodies. SolidWorks was chosen for its reliable parametric functionality, advanced assembly management, and suitability for multi-part anatomy modeling. Preliminary forearm shaping using lofted cross-sections was also explored.

3.3 3D Designing of the Hand and Forearm

Designing started with the forearm, using an elliptical cross-section inspired by research [2]. The study used one forearm circumference and 17 planes to approximate the shape. To improve customization and realism, this project used five circumference values at 0%, 25%, 50%, 75%, and 100% of the forearm length, along with 20 planes. These inputs enabled finer shape control. The values were entered into Excel to interpolate at other planes. The referenced paper [2] used cubic equations to define axes for supination and pronation. the equations provided for the supination position were selected and applied.

Normalized axis values were calculated with cubic polynomial expressions across 20 design planes. Afterward, actual axis dimensions were found by multiplying normalized values by the forearm circumference at each plane, using Excel with interpolated circumference data. These values enabled accurate ellipse creation in CAD, where ellipses were positioned on separate planes in SolidWorks. To estimate circumferences at intermediate planes, the FORECAST.LINEAR function in Excel was used for linear interpolation, providing perimeter estimates for elliptical sections in the CAD model. The ellipses were spaced evenly along the forearm's axis, connected via the Loft tool to form the final smooth outer surface.

3.4 Assembly of the Complete Hand Design

The forearm, palm, and fingers were imported into SolidWorks, aligned, and connected with geometric mates for accurate anatomy. The design was tested to ensure parameter changes updated the whole model. Fully assembled hand and forearm model in SolidWorks, showing aligned finger joints, palm structure, and forearm connection

Phase 2

The previous model was used to create a lightweight, breathable cast that immobilizes fractures effectively and improves wearability and hygiene over traditional plaster casts. Using a parametric model, advanced design, and mesh editing, a functional, 3D-printed cast was developed. The process began with a precise parametric model of the fractured forearm, used as an accurate base for creating the personalized cast. This model was then exported in STL format for use with mesh editing software. Meshmixer was chosen for its ability to process anatomical scans, sculpt organic shapes, remesh, and prepare files for 3D printing. The cast was designed as a shell covering only necessary areas, following the physician's guidance.

The selection tool was initially used to outline the arm and hand for the cast, employing a sphere brush with adjustable size for precision in narrow or broad areas. Edges were smoothed with increased boundary smoothness and iterations, preserving group boundaries and adjusting border rings. Only essential parts of the arm and hand, like the forearm and wrist, were included to reduce material and improve comfort. An offset model was designed with a 1.5-2.5 mm clearance to prevent skin contact and accommodate swelling, achieved via an extract offset operation. The cast was separated from the arm model in Meshmixer, smoothing added to improve mesh quality, especially around the thumb, wrist, and cast end. For breathability and hygiene, perforations with varying density were added, thicker near support zones, thinner elsewhere. Mesh reduction tools simplified the cast, with targeted refinement in critical areas to maintain accuracy while optimizing for printing and comfort..

Ventilation patterns were integrated into the cast surface, avoiding high-stress zones, rigidity regions, and the boundary dividing the cast into two halves. Patterns were omitted along the split plane, outer edges, and joint areas to preserve integrity. This targeted placement optimized airflow and mechanical performance, maintaining the cast's rigidity, fit, and printability while enhancing comfort with ventilation channels.

To enable easy donning and doffing, the model was sliced by first breaking the mesh into sections with separate shells, then using a “Plane Cut” along the forearm's longitudinal axis to create two symmetrical halves. Mesh defects were repaired to ensure printability and structural integrity.

After fixing the mesh, the halves were imported into PrusaSlicer for printing, positioned separately for optimal orientation, with organic supports added to reduce material use cleanup.

The finalized G-code was then exported and transferred to the 3D printer to begin the fabrication process. The finalized G-code ran on a Prusa 3D printer using settings from PrusaSlicer. A roll of PLA filament in the desired colour was loaded into the machine before printing. A 0.4 mm nozzle diameter was used for a solid balance between detail and speed. The layer height was set to 0.2 mm, providing enough surface quality while keeping the print time reasonable. The infill density was adjusted to 15%, as per the slicing phase.

4. RESULTS AND DISCUSSION

Phase 1

An Excel spreadsheet was created as an input interface for user-specific measurements like palm width, finger lengths, and forearm dimensions. Instead of using the SolidWorks API, the sheet is directly linked to the parametric model, allowing automatic updates when values are entered. A simple GUI was designed to help users input measurements correctly and trigger real-time 3D hand model customization.

Forearm Length(mm)	Plane	Region	Position	Forearm Circumference (mm)
250				
	Front Plane			
	1	0% Elbow	0	500
	2	25% Upper Forearr	0.25	520
	3	50% Mid Forearm	0.5	510
	4	75% Lower Forearr	0.75	500
	5	100% Wrist	1	490
	6			
	7			
	8			
	9			
	10			
	11			
	12			
	13			
	14			
	15			

Figure 1: Simple graphical user interface (GUI) designed to collect patient-specific measurements.

Simple graphical user interface (GUI) designed to collect patient-specific measurements. The GUI was built to allow non-technical users to input data easily, ensuring real-time updates to the 3D model. (Forearm).

To identify patterns in hand dimensions, palm parameters like width, height, and circumference are considered. A separate GUI for the hand component can also be created, allowing independent entry of palm parameters for precise 3D hand model customization, reflecting anatomical variations. Data show that forearm circumferences at normalized positions (0%, 25%, 50%, 75%, 100%) fall within well-defined ranges among 30 participants. Each position's circumferences are confined between min and max values, indicating limited variation at those sections.

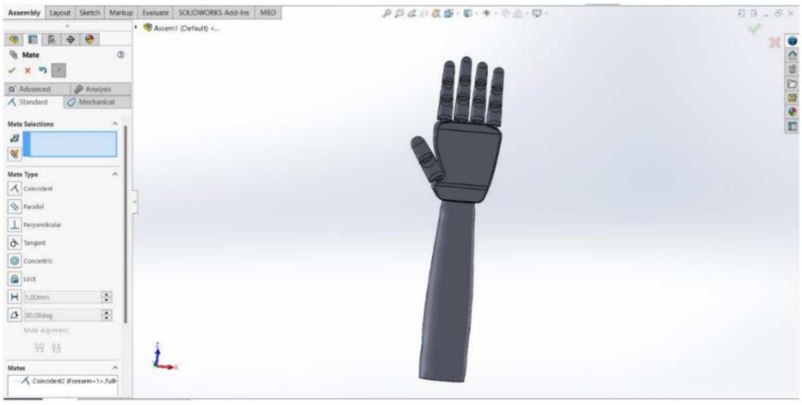


Figure 2: Fully assembled hand and forearm model in SolidWorks showing aligned finger joints, palm structure, and forearm connection.

Measuring circumferences at 0%, 25%, 50%, 75%, and 100% positions reveals a gradual decrease from elbow to wrist, reflecting typical forearm tapering. Minor individual variations show subtle anatomical differences, but the overall trend is consistent. This bounded variation indicates that adult forearm geometry follows predictable limits, even across a mixed-gender group aged 25–38. These findings imply that anthropometric measurements are inherently constrained, which is vital for creating accurate 3D hand and forearm models. The model incorporates upper and lower parameter limits based on these ranges to avoid unrealistic geometries. Natural bounds in data ensure these constraints are practical, accommodating individual differences while maintaining overall shape and function. Consequently, the parameter limits are both biologically justified and essential for realistic, patient-specific models

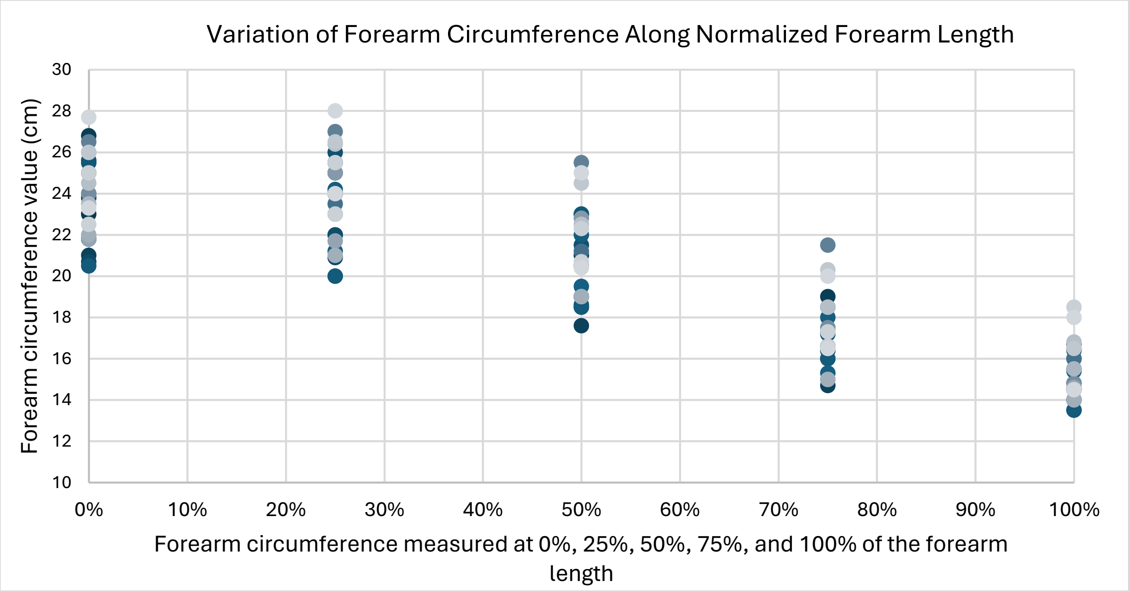


Figure 3 Variation of Forearm Circumference Along Normalized Forearm Length

Phase 2

The cast was printed using a Prusa i3 MK32S+ 3D printer with the following parameters: 200°C nozzle temp, 60°C bed temp, 0.4mm nozzle, PLA material. Each print took 5-6 hours, using 140g PLA costing Rs 1000. Supports removed and edges sanded with post-printing.

Figure 4a: Forearm cast with additional smoothing

Figure 4b: Number of triangles changed as required

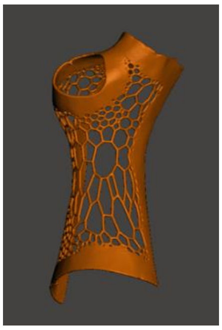


Figure 4c: Sliced cast along the selected plane

Figure 4d: The two halves of the 3D printed orthopedic forearm cast

Mechanical tests on PLA, including two tensile strength tests on cylindrical samples (fig 5), showed a breaking force of 0.4 kN in mechanical tensometer testing, indicating PLA's adequate strength for orthopedic casts, with the benefits of reduced weight and enhanced comfort.Experimental setup which was used to measure the linear samples (fig 6) recorded a breaking force of 63 N in semi-computerized tensometer testing. This result supports the previous findings and confirms that PLA exhibits adequate mechanical strength for use in orthopedic casts. It can thus be concluded that PLA is a reliable and effective material for producing patient-specific 3D-printed orthopedic immobilization devices. Mechanical testing of the 3D-printed cast was conducted using a semi-computerized tensometer. During horizontal compression testing, a load of 10 N was applied. The cast reached its breaking point at this applied load, indicating the maximum compressive strength it could withstand under the given testing conditions.

Figure 5: Sample designed in fusion 360 and 3D printed sample

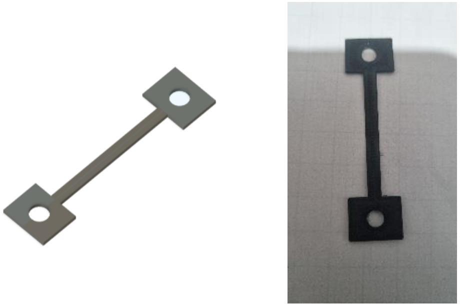


Figure 6: sample designed in Fusion 360 and 3D printed sample

Dimensions of the tested samples

Type of Sample		Radius(mm)	Length(mm)	Breath(mm)	Width(mm)
Cylindrical Sample		07.00(outer) 05.00(inner)	08.00 (outer) 16.00(middle)	-	-
Linear Sample		02.50	15.00(outer) 40.00(middle)	12.00(outer) 04.00(middle)	0.60

*The dimensions of the forearm cast vary along the arm, with a uniform thickness of 5.00mm

The discrepancies between the tensile results of the cylindrical sample tested using a mechanical tensometer and the linear sample tested using a semi-computerized tensometer are due to the shape and dimensions of the samples used. The results confirm that cylindrical shapes made of PLA could withstand greater tensile force than linear shapes. Since 3D printed parts are made from layers and non-homogenous this may lead to different results.

5. CONCLUSION

This study demonstrates a parametric approach for generating anatomically accurate and biologically valid 3D hand and forearm models using anthropometric measurements integrated with CAD and additive manufacturing. Based on this framework, a lightweight, ventilated, and patient-specific 3D-printed forearm cast was successfully designed and fabricated using PLA. Mechanical testing confirmed that the material provides sufficient strength for non-surgical fracture management. Clinical testing and validation, along with further functional enhancements, are identified as important directions for future work to support clinical adoption.

6. REFERENCES

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