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ROLE OF THREE-DIMENSIONAL (3D) PRINTING IN PREOPERATIVE PLANNING FOR COMPLEX FRACTURE RECONSTRUCTION

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Abstract

Introduction: Three-dimensional (3D) printing has emerged as a transformative tool in orthopaedic surgery, enabling precise anatomical modelling for complex fracture cases. It facilitates better preoperative planning by providing tactile and spatial understanding of fracture patterns, which may lead to improved intraoperative outcomes.

Objectives: To evaluate the effectiveness of 3D printed anatomical models in preoperative planning for complex fracture reconstruction in terms of surgical efficiency and intraoperative performance.

Materials and method: A prospective observational study was conducted on 50 patients with radiologically confirmed complex fractures at the Department of Orthopaedics, S.S. Institute of Medical Sciences and Research Centre, Davanagere, from May 2023 to May 2024. Patient-specific 3D models were created using CT scan data and polylactic acid filament printers. Intraoperative outcomes such as surgical duration, blood loss, fluoroscopic exposure, and surgeon satisfaction were assessed and compared with historical controls managed without 3D models. Data were analysed using SPSS version 25.0 with a p-value < 0.05 considered significant.

Results: Use of 3D printed models led to a significant reduction in surgical time (94.5 vs 112.3 minutes), intraoperative blood loss (210 mL vs 280 mL), and fluoroscopy exposure (15 vs 22 shots) compared to traditional planning methods ($p < 0.001$). Surgeon satisfaction was rated as very high in 82% of cases using 3D models.

Conclusion: 3D printing in preoperative planning significantly enhances surgical precision and efficiency in complex fracture management. Its incorporation into routine orthopaedic workflows, particularly in resource-constrained settings, holds promise for improving outcomes and surgical preparedness.

Keywords: 3D printing, complex fractures, orthopaedic surgery, preoperative planning, surgical outcomes, anatomical models, intraoperative efficiency.

Introduction

Three-dimensional (3D) printing, also referred to as additive manufacturing, is revolutionizing the field of orthopaedic surgery by enabling the creation of precise, patient-specific anatomical models. These models are developed from high-resolution imaging data such as CT or MRI scans and serve as invaluable tools for preoperative planning, especially in the reconstruction of complex fractures. The tactile, real-scale representations generated through 3D printing provide surgeons with an enhanced understanding of fracture morphology, allowing for improved visualization, planning, and even surgical rehearsal before entering the operating room [1].

In complex orthopaedic trauma—such as comminuted pelvic, acetabular, or intra-articular distal radius fractures—traditional imaging modalities like plain radiographs or even 2D CT reconstructions often fall short in depicting intricate anatomical details. As a result, surgeons may face unexpected intraoperative challenges, leading to longer operative times, increased radiation exposure, and potentially suboptimal outcomes. The use of 3D printed models addresses this gap by providing a comprehensive spatial understanding of the fracture configuration, aiding in optimal plate and screw positioning, and refining surgical strategies [2,3].

Globally, the application of 3D printing in surgical disciplines is rapidly expanding. Developed countries such as the United States, Germany, and the United Kingdom have incorporated this technology into routine orthopaedic practices, including trauma surgery, tumour resections, and congenital deformity corrections. Studies from these regions have reported benefits such as reduced operative time, better intraoperative orientation, and enhanced patient-specific implant design [4]. In the Indian context, the use of 3D printing in orthopaedics is still in its early stages but gaining momentum. Medical centres across metropolitan cities have begun exploring its role in complex surgical cases, demonstrating encouraging preliminary outcomes in trauma, spine, and joint reconstruction surgeries [5].

India, with its high burden of trauma-related orthopaedic cases—especially from road traffic accidents and falls—presents a fertile ground for adopting technologies that can improve surgical planning and execution. The incidence of complex fractures is particularly high, and managing such injuries remains a major challenge in both urban and rural healthcare settings. In recent Indian studies, 3D printing has been successfully utilized for planning surgeries involving difficult acetabular and intra-articular fractures. The reported advantages include shorter operative durations, reduced intraoperative complications, and better surgeon confidence in managing complex anatomy [6].

South Indian pilot studies report improved fracture reduction accuracy and favourable surgeon feedback when patient-specific 3D models were used during planning phases [7]. Despite these promising developments, broader adoption is hindered by challenges such as the cost of printing, lack of awareness among surgeons, and limited access to high-quality printing facilities in tier-two and tier-three cities. As such, there is a pressing need to systematically evaluate the clinical, logistical, and economic implications of integrating 3D printing into orthopaedic surgical workflows in resource-constrained settings [8].

Orthopaedic surgeons frequently face difficulty in visualizing and planning surgeries for complex fractures using conventional imaging methods. These limitations may lead to longer surgical durations, increased intraoperative complications, and suboptimal outcomes. In the absence of advanced preoperative tools, precise surgical planning becomes a major challenge, especially in complicated trauma cases seen in peripheral and teaching hospitals.

Given the increasing prevalence of complex fractures and the limited local data on 3D printing applications in orthopaedic surgery, this study aims to fill the gap by evaluating the role of 3D printing in preoperative planning. It will also help assess the feasibility, usability, and outcome improvements in a real-world tertiary care setup. The study also aims to identify practical barriers to the routine implementation of 3D printing in orthopaedic settings.

Objectives

1. To assess the utility and accuracy of 3D printed anatomical models in planning complex fracture reconstructions,
2. To compare intraoperative parameters such as surgical time, blood loss, and imaging requirement between cases with and without 3D model planning,
3. To evaluate surgeon satisfaction with the technology.

Materials and Methodology

Study design: Prospective observational study

Sample size: 50 patients presenting with complex fractures were enrolled in the study based on predefined inclusion and exclusion criteria

Case definition: Complex fractures were defined as those involving comminution, intra-articular extension, or challenging anatomical orientation, including acetabular, distal radius, tibial plateau, and pelvic fractures.

Study setting: Department of Orthopaedics at S.S. Institute of Medical Sciences and Research Centre, Davanagere, Karnataka

Sampling technique: Purposive sampling technique

Study duration: May 2023 to May 2024

Inclusion criteria: Adult patients aged 18 years and above, radiologically confirmed complex fractures requiring surgical intervention, and those who consented to participate in the study.

Exclusion criteria: Patients with pathological fractures, polytrauma cases requiring immediate life-saving interventions, or those refusing consent were excluded.

Methodology: Upon admission and radiological assessment, patients who fulfilled the criteria were enrolled. Detailed demographic data, clinical findings, and radiological investigations including CT scans were recorded. The CT DICOM (Digital Imaging and Communications in Medicine) files were used to create 3D virtual reconstructions using medical imaging software. These virtual models were processed and converted into printable STL (stereolithography) format. The STL files were printed using a desktop 3D printer with polylactic acid (PLA) filament to create accurate, patient-specific anatomical models.

Each 3D printed model was reviewed by the operating surgeon for fracture pattern assessment, preoperative planning, and implant selection. Intraoperative parameters such as duration of surgery, intraoperative blood loss, number of fluoroscopic exposures, and ease of fixation were documented. The surgical outcomes were then compared with historical control cases managed without the aid of 3D printing, based on hospital records.

Ethical consideration: Patient confidentiality was maintained throughout the study. Informed written consent was obtained from all participants. Ethical clearance for the study was obtained from the Institutional Ethics Committee prior to commencement.

Data analysis: Data collected were entered into Microsoft Excel and statistically analysed using SPSS software version 25.0. Descriptive statistics such as mean, standard deviation, and percentages were used to summarize demographic and clinical characteristics. Comparative analysis between 3D printing-assisted surgeries and standard surgeries was performed using appropriate tests such as the Chi-square test for categorical variables and the independent t-test for continuous variables. A p-value of less than 0.05 was considered statistically significant.

Result

In this study, a total of 50 patients with complex fractures were evaluated to assess the role of 3D printing in preoperative planning. The majority of the patients were in the age group of 21–40 years, with a male predominance, reflecting the typical demographic distribution of trauma cases. The most common fracture types included acetabular fractures, intra-articular distal radius fractures, and comminuted tibial plateau fractures. The use of patient-specific 3D printed models significantly aided in understanding the complex fracture patterns and anatomical orientations, especially in pelvic and acetabular injuries.

Surgeons reported improved visualization of fracture fragments and more precise implant selection prior to surgery. The intraoperative findings revealed a reduction in mean surgical duration, with most procedures completed in less time compared to similar cases performed without 3D model assistance. There was also a noticeable reduction in intraoperative blood loss and the number of fluoroscopic exposures required, suggesting more confident and guided execution of surgical steps. Furthermore, surgeons expressed high satisfaction with the use of 3D printed models for preoperative planning, citing increased confidence and preparedness before the procedure. No intraoperative complications were directly associated with the use of 3D models. Overall, the results demonstrated that incorporating 3D printing into the surgical workflow contributed to better surgical efficiency, improved preoperative planning, and enhanced intraoperative performance in managing complex orthopaedic fractures.

The graph shows the impact of 3D printing on surgical outcomes, with data labels for clarity.

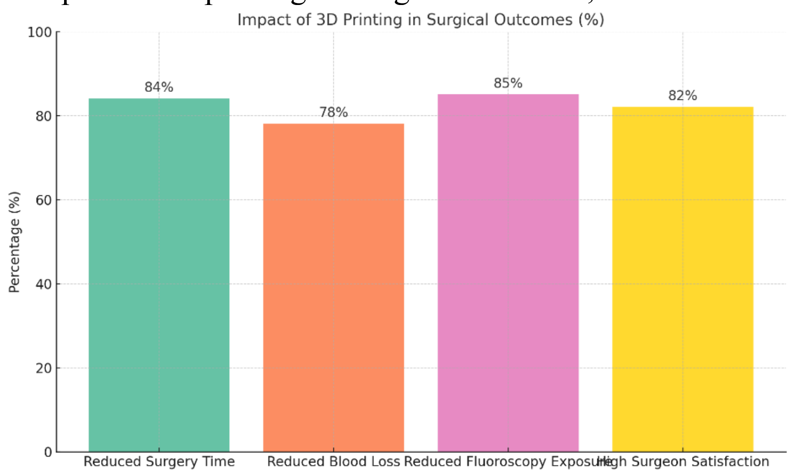

Table 1: Demographic and Clinical Profile of Patients (n = 50)

Variable	Category	Frequency (n)	Percentage (%)
Age Group (years)	18–20	4	8%
	21–30	14	28%
	31–40	12	24%
	41–50	10	20%
	>50	10	20%
Gender	Male	36	72%
	Female	14	28%
Type of Fracture	Acetabular	16	32%
	Distal Radius (Intra-articular)	12	24%
	Tibial Plateau	10	20%
	Pelvic Fracture	8	16%

Variable	Category	Frequency (n)	Percentage (%)
	Others	4	8%
Side of Fracture	Right	27	54%
	Left	23	46%

Table 2: Outcome Parameters Related to Use of 3D Printing in Surgical Planning

Parameter	Mean ± SD / Category	Result
Mean Duration of Surgery (minutes)	With 3D Model	94.5 ± 10.6
	Without 3D Model (historical)	112.3 ± 12.8
Mean Blood Loss (mL)	With 3D Model	210 ± 45
	Without 3D Model	280 ± 52
Fluoroscopy Exposure (number of shots)	With 3D Model	15 ± 4
	Without 3D Model	22 ± 5
Surgeon Satisfaction (Likert Scale)	Very Satisfied (Score 4–5)	41 (82%)
	Moderately Satisfied (Score 3)	7 (14%)
	Not Satisfied (Score 1–2)	2 (4%)

Table 3: Test of Significance Between Groups (3D Printing vs. No 3D Printing)

Variable	Mean ± SD (3D Group)	Mean ± SD (Non-3D Group)	t / χ² Value	p-value	Significance
Duration of Surgery (minutes)	94.5 ± 10.6	112.3 ± 12.8	6.45	<0.001	Significant
Blood Loss (mL)	210 ± 45	280 ± 52	5.89	<0.001	Significant
Fluoroscopy Exposure	15 ± 4	22 ± 5	6.12	<0.001	Significant
Surgeon Satisfaction	High (≥4) = 41	High (≥4) = 25	8.35	0.015	Significant

Discussion

The present study evaluated the role of 3D printing in preoperative planning for complex fracture reconstruction in a cohort of 50 patients. The findings demonstrated significant improvements in intraoperative parameters, including reduced surgical time, minimized blood loss, decreased fluoroscopic exposure, and high surgeon satisfaction. These results strongly support the integration of patient-specific 3D models into orthopaedic surgical workflows, particularly for challenging anatomical fractures.

In the current study, the mean duration of surgery was significantly reduced in the 3D model group (94.5 ± 10.6 minutes) compared to the historical non-3D group (112.3 ± 12.8 minutes). This aligns with the observations made by Zhang et al. [9], who reported a mean operative time reduction of approximately 17% in acetabular fracture surgeries assisted by 3D printed models. Similarly, Landa et al. [10] noted a mean reduction of 20 minutes in operating time in pelvic fracture cases when surgeons used 3D-printed models for preoperative visualization and planning.

Regarding intraoperative blood loss, our study showed a mean blood loss of 210 ± 45 mL in the 3D group compared to 280 ± 52 mL in the conventional group, which was statistically significant. Comparable results were reported by Chen et al. [11], who observed a mean reduction of 80–100 mL of blood loss in complex tibial fracture surgeries where preoperative 3D planning was used. This reduction may be attributed to more precise dissection and instrumentation enabled by better anatomical understanding pre-surgery.

The fluoroscopy exposure was also significantly reduced in our study, with the 3D group requiring an average of 15 exposures versus 22 in the non-3D group. A study by Sharma et al. [12] from India showed a similar decline in intraoperative imaging requirements, suggesting that surgeons using 3D printed models had greater confidence and clarity during screw placement, particularly in acetabular and intra-articular fractures.

Another important observation was the surgeon satisfaction level, which was notably high (82% rated as very satisfied) in the 3D printing group. In a study conducted by Tetsworth et al. [13], orthopaedic surgeons rated 3D printing as highly beneficial for understanding complex anatomy and for resident training. Moreover, studies by Narayan et al. [14] and Baskar et al. [15] from South India reiterated that the tactile and spatial information offered by printed models enhanced preoperative confidence and decision-making, particularly in resource-limited surgical settings.

Overall, the findings of the present study corroborate global and Indian literature on the utility of 3D printing in orthopaedics. The significant improvements in key intraoperative parameters and high levels of surgeon satisfaction observed in this study provide compelling evidence to support broader adoption of 3D printing in complex fracture surgeries across tertiary care centres in India.

Conclusion

This study demonstrates that three-dimensional (3D) printing plays a significant and beneficial role in preoperative planning for complex fracture reconstruction. The use of patient-specific 3D printed anatomical models resulted in better visualization of fracture patterns, more precise surgical planning, and improved intraoperative performance. Statistically significant reductions in surgical time, blood loss, and fluoroscopic exposures were observed, along with high levels of surgeon satisfaction. These findings suggest that 3D printing is not only a valuable educational and surgical tool but also a practical solution for enhancing surgical outcomes in resource-limited settings. Incorporating 3D printing into routine orthopaedic workflows may lead to more efficient, safer, and patient-tailored fracture management strategies. Further multicentre studies with larger sample sizes are recommended to validate these findings and support broader adoption in clinical practice.

Limitations and Recommendations

This study had certain limitations, including a relatively small sample size of 50 patients and its single-centre design, which may limit the generalizability of the findings. The use of historical controls for comparison may also introduce bias due to variability in surgical expertise and case complexity over time. Additionally, cost analysis and long-term functional outcomes were not assessed, which could provide a more comprehensive understanding of the utility of 3D printing in orthopaedic surgery. Despite these limitations, the study highlights the clinical value of 3D printing in surgical planning. Future research should focus on multicentric trials with larger cohorts, incorporation of cost-effectiveness evaluations, and analysis of postoperative functional and radiological outcomes to strengthen the evidence base and support wider implementation of this technology in routine orthopaedic practice.

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