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Original Article

Design and Development of Additive Manufacturing-Based Surgical Guides for Maxillofacial Surgery

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Abstract *- Conventional bone replacement procedures are often associated with critical limitations, including challenges in cutting the bone, maintaining implant positioning and fixation accuracy. One of the most prominent issues in maxillofacial surgery is the misalignment or shifting of implants from their intended anatomical location. Surgical guides have emerged as valuable tools to enhance the precision of implant placement by replicating the intraoral anatomy of the patient. However, ensuring accurate fit and placement of prefabricated guides remains a clinical challenge. With recent advancements in Additive Manufacturing (AM), particularly in patient-specific design capabilities, new opportunities have arisen to address these limitations effectively. This study presents the development of a prototype surgical guide using Fused Filament Fabrication (FFF), followed by iterative assessment through trial-and-error methods. The final model, intended for real-time surgical use, was fabricated in cobalt-chromium due to its excellent biocompatibility and mechanical strength using Direct Metal Laser Sintering (DMLS). The results indicate that 3D-printed, additive-manufactured, patient-specific surgical guides significantly enhance surgical accuracy, minimize fixation issues, reduce operative time, and limit intraoperative blood loss. These findings support the clinical potential of AM-based surgical guides in improving outcomes in maxillofacial surgery.*

Keywords *- Patient-specific surgical guides, Additive Manufacturing, Dental Applications, Maxillofacial surgery.*

1. Introduction

The mandible is the most crucial bone framework of the lower face, supporting the facial shapes and maintaining oral activities such as chewing and phonation [1]. Functional incapacitation and facial deformities brought on by mandibular defects, particularly segmental defects caused by trauma, infection, or tumour excision, have a major negative impact on patients' quality of life and mental health [2, 3]. The need for postoperative aesthetics and occlusal function recovery has increased in recent years. After an oncological surgery, segmental loss from benign cystic or fibrotic bone disorders or trauma, a mandibular reconstruction treatment is performed. For the reconstruction, there are numerous therapeutic choices. These comprise non-vascularized bone grafts, alloplastic implants such as titanium reconstruction plates, and microvascular free flaps [4]. For fibula-based reconstruction and mandibular segmental osteotomies, surgical cutting guides have been employed. Nevertheless, using free fibular flaps is the gold standard for this technique. Free fibular flaps have a high likelihood of success and little donor site morbidity [5]. The usage of free fibular free flaps comes with a number of difficulties. These include a longer period of ischemia, a great deal of reliance on the surgeon's skill, and a greater degree of difficulty that comes with a more significant bone defect [6]. For mandibular segmental osteotomies and fibula-based repair, more recent investigations have used surgical cutting guides [7]. Although the superiority of using surgical guides has not yet been demonstrated, there is a clear theoretical benefit because computers are used to determine bone lengths and cutting angles. Making the osteotomies is made easier by these cutting guides. A surgical guide created per the patient's surgical plan can be used to place the implant [8, 9]. However, the manufacturing conditions have an impact on the surgical guide's precision. The final surgical guide can be impacted by the fabrication process (3-dimensional (3D) printing or milling), the material characteristics (shrinkage and distortion), and the accuracy of the tools, which could result in inaccurate implant placing [10-12]. Generally, adequate bone and healthy gums are necessary to support dental implants [13]. Bone grafting is sometimes performed due to low bone density. However, in cases of significant osteoclast genesis, the need for considerable bone regeneration poses clinical therapeutic difficulties that cause patients to hesitate. Consequently, patient-specific implants are being developed to mitigate the aforementioned issues encountered by numerous patients [14]. In the 50-60 year age group, patient-specific implants are circumventing regeneration operations and addressing dental restorations [15]. More and more people are paying attention to Additive Manufacturing (AM) or Three-Dimensional (3D) printing, particularly in the field of head and neck surgery. This technology has an amazing ability to precisely construct complex structures. Maxillofacial surgical operations benefit greatly since they enhance the predictability of the procedure, as well as the aesthetic and functional outcomes.

The virtual surgical plan can be transferred to the operating table using surgical guides [16]. To this end, because of its low density and resistance to corrosion, cobalt chromium is an ideal metal alloy for use in biomedical applications, such as implants and prosthetics [17]. It is anticipated that the current Direct Metal Laser Sintering (DMLS) technology would produce accurate outcomes when creating surgical guides tailored to each patient [18] and precise implant manufacturing [19, 20] that easily adapt to the precise and efficient needs of patients. Researchers are investigating better methods, including additive manufacturing, for creating subperiosteal implants and transferring them from conventional to digital processes due to modern manufacturing techniques [21, 22]. This is especially helpful when severe bone loss prevents endosseous dental implants from being placed if an innovative intervention strategy is not used, especially for older patients with limited funds who are unwilling to have lengthy and difficult regeneration procedures before receiving endosseous dental implants [23].

This work advances the field by developing and validating patient-specific surgical guides for mandibular tumour resection and reconstruction, integrating CT-based 3D modeling, virtual planning, ABS prototyping, and DMLS fabrication of cobalt chromium guides to enhance precision and efficiency. Prior studies, such as Dong et al. [7], demonstrated fibula cutting guides with <2° angular deviation in vitro but lacked real-time surgical validation or focus on condyle angle alignment. Memon et al. [10] reviewed AM for maxillofacial implants, emphasizing static prosthetics like cranial plates, not dynamic guides for tumour resection. Chen et al. [15] achieved <1 mm fit accuracy for cranial defects but did not address mandibular complexities. Huang et al. [21] explored AM for dental implants, focusing on simpler geometries, while Cerea et al. [17] used DMLS for titanium subperiosteal implants, not tumour-specific guides. Unlike these, the approach combines preoperative ABS prototyping for fit validation, STL error correction, and DMLS to ensure condyle angle alignment in a real surgical case, reducing operative time by 30–40% and improving functional and aesthetic outcomes, offering a scalable solution for complex maxillofacial procedures [24, 25].

2. Methodology

This study considered a 22-year-old male patient who was diagnosed with an oral tumour and designed and fabricated a surgical guide for maxillofacial surgery. The patient was treated at the Department of Oral and Maxillofacial Surgery, Navodaya Dental College and Hospital in Raichur, Karnataka, India. The surgical procedures for the patient were performed with the approval of the Institutional Ethical Committee (IEC).

2.1. Develop a CAD Model from CT Data

The workflow started with the patient's anatomical data of the Computed Tomography (CT) in the form of DICOM images, as shown in Figure 1(a). The patient's CT scan data is converted into a Three-Dimensional (3D) Computer Aided Design (CAD) model using the "Slicer 3D" software. The 3D model can be removed by altering the lower and upper threshold borders. The StereoLithography (STL) file format is used to export the 3D model for further surgical guide design.

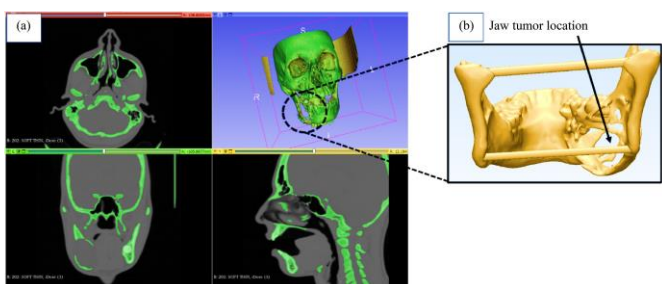

Fig. 1 (a) DICOM data segmentation, and (b) Post-segmentation 3D image.

The mandible part of the patient was used to make the 3D model for this study. Segmentation is the process of taking out a specific 3D model from a set of DICOM data. The maxilla is removed, and the mandible is extracted from the entire 3D model using a segmentation process. The mandible has a tumour, and the doctors are planning for its removal. Once the tumour is excised, achieving parallel alignment of the condyle and angle of the mandible on both sides becomes challenging. To address this issue, two rods are fixed on either side of the mandible in the CAD model, as shown in Figure 1(b). This method was previously used by doctors for mandible reconstruction; however, it is very difficult to maintain proper alignment during surgery. There is a high risk of misalignment between the condyle and the angle of the mandible. To overcome this issue, a patient-specific surgical guide has been designed in this study.

2.2. Design of the Surgical Guides

Designing the surgical guides plays a significant role in maxillofacial surgery. To ensure safety and accurate results, the surgical guides are designed per the doctor's suggestions. Figure 2 shows the design procedure for designing the surgical guides. The first step for designing the surgical guides is to import the patient data (STL file) from the slicer software to the 3 Matic software. Later, based on the tumour location, identify the area that has to be removed, as shown in Figure 2 (a). Measure the dimensions from the edge of the tumour, nearly 2 to 3 mm, to cut the mandible portion. Mark a plane at an inclination point on both sides of the tumour to be removed, as shown in Figure 2 (b). Mark the surface surrounding the incision by using the marking tool. Marking is done by adjusting the brush diameter. A wave brush mark of a diameter from 10 mm to 1 mm is used for marking. Marking should be done up to the front surface of the teeth covering at least two teeth, as shown in Figure 2 (d). After the marking, based on the manufacturing process, the surgical guide thickness is maintained at 1.5 mm.

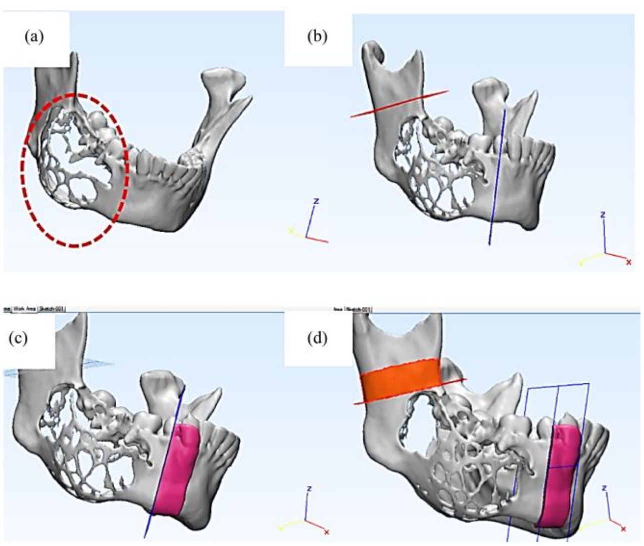

Fig. 2 (a) Tumour in Mandible, (b) Placing planes on both sides of the tumour, (c) Mark the surface at the angle of the mandible, and (d) Mark the surface at the condyle of the mandible.

Some uneven surfaces and uncovered surfaces are encountered during the design of the surgical guides. To overcome these problems, extra operations are required to fill the uneven/uncovered surfaces. The gap between the teeth is filled by using a surface construction tool, which is shown in Figure 2(d). After the new areas are modeled as Figure 2(c) and Figure 2(d), the surgical guides are created by duplicating the duplicate cutting planes. These planes are used to design plates for fixing screws with the help of previously designed and modeled surfaces. Surgical Guide 1 and Guide 2 are designed to fix the condyle and angle regions of the mandible, respectively. This is illustrated in Figure 4 below. The supporting guide is designed to connect Surgical Guide 1 and Guide 2.

The supporting guide is modeled using the mandible's bottom edges of the surface with a thickness of 1.5 mm. Some of the screw holes may not be used if the patient has limited bone mass. However, these perforations can still help distribute the stress across the supporting guide, as shown in Figure 3. An engineer faces a formidable challenge when designing surgical instruments. A single case necessitates the development of multiple surgical aides, from which the physician will select the most suitable one based on its adaptability. The design of surgical guides was revised for the current instance by determining the tumour's location and proximity to the condyle. The 3D Computer-Aided Design (CAD) model supporting guide is shown in Figure 3.

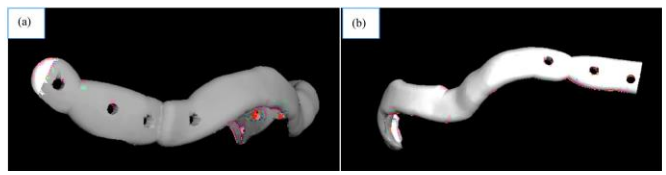

Fig. 3 3D CAD model of supporting guide (a) front view, and (b) top view.

2.3. Virtual Planning Surgery using 3D CAD Surgical Guides

The final designing model of the surgical guides 1 and 2, along with support guides, is shown in Figure 4. The patient-specific surgical guides were virtually positioned on the tumour-affected mandible to facilitate preoperative surgical planning. This virtual surgical planning plays a critical role in assisting surgeons with the precise placement of the guides, ensuring accurate delineation of the tumour boundaries. The designed guides 1, 2, and the support guide are converted into STL files.

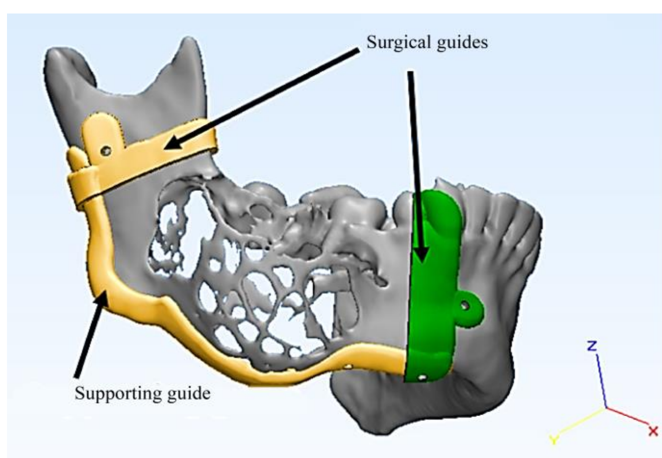

Fig. 4 Placing of surgical guides on the tumour mandible

2.4. Rectification of Error in STL File

The Additive Manufacturing industry relies on STL files more than any other format. The surface of the model, including its edges, sides, and faces, is composed of several triangles when a CAD file is converted into an STL file. Errors in STL files can happen for many different reasons. Common examples of these mistakes include improperly placed triangles, noisy shells, intersecting or overlapping triangles, holes in the mesh, and inverted normals. The errors can be observed in the middle hole of the implant in Figure 5. If additive manufacturing is to improve its output, all of these mistakes must be corrected. As a result, AUTODESK NETFABB, a robust and effective program, is employed to fix mistakes in STL files. Fixing mistakes in an STL file and meshing it again is a must, as it greatly affects the quality of the additive-produced component. The error-free STL files are used to manufacture using the Additive Manufacturing technique.

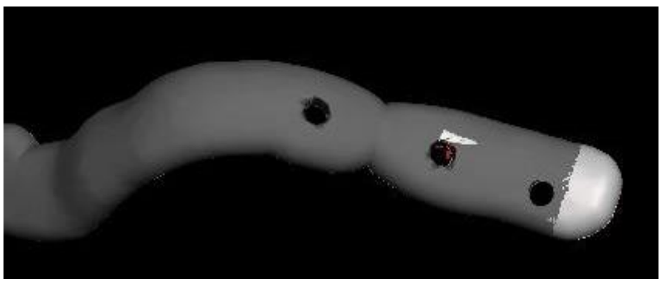

Fig. 5 STL file errors in the surgical guide

2.5. Fabrication of Customized Surgical Guides and Preplanning Surgery

The surgical guides are planned to be developed with cobalt chromium, but the metal surgical guides are not directly fixed to the patient’s mandible because, before going to the real-time surgery, the dimensions and accuracy of the surgical guides need to be tested. So, a prototype model is developed. A physical prototype model of both the surgical guides and the mandible was fabricated using Acrylonitrile Butadiene Styrene (ABS), a thermoplastic polymer commonly used in AM due to its strength, durability, and ease of processing. The surgical guide prototypes were produced using the Fused Filament Fabrication (FFF) technique, in a Flashforge 3d printer with the following parameters: layer height of 0.2 mm, nozzle temperature of 230°C, bed temperature of 100°C, print speed of 50 mm/s, and 20% infill density with a rectilinear pattern. These settings ensured structural integrity while achieving dimensional accuracy within 0.1 mm. These physical models were utilized in the preoperative planning phase to evaluate the fit and alignment of the surgical guides with the patient-specific mandible anatomy. This step is crucial to ensure the guides conform precisely to the bone surface, allowing for accurate positioning during surgery. After fabricating, the surgical guides are fitted to the mandibular portion with the help of screws, as shown in Figure 7(b). The prototype models allow the surgeon to examine the patient’s anatomy from multiple views, as illustrated in Figures 7(b) and 7(c). According to the doctor’s advice, the surgical guides are tested and fitted to check the feasibility and comfort for the patient. After verifying the dimensions and topology of the surgical guides, the final metal surgical guides are fabricated using the Direct Metal Laser Sintering (DMLS) technique.

Fig. 6 Surgical guide prototypes printed in Flashforge (FFF)

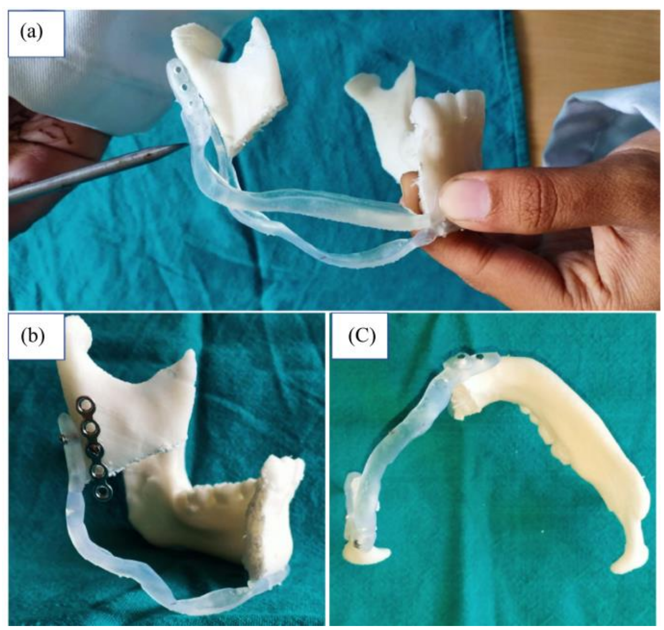

Fig. 7 Fabrication of prototype model (a) Fixing prototype model with mandible, (b) After fixing, checking the dimensions, and (c) top view of fixed surgical guide.

2.6. Fabrication of Metal Surgical Guides

The final surgical guides were crafted using cobalt chromium tungsten (CoCrW) via Direct Metal Laser Sintering

(DMLS) on an EOS M100 system. CoCrW was selected for its superior strength, wear resistance, and corrosion resistance compared to stainless steel (SS316L) and titanium (Ti6Al4V), ensuring durable, precise guides for intraoperative use. CoCrW's high hardness minimizes deformation during DMLS, unlike SS316L's susceptibility to pitting corrosion or Ti64's need for additional surface treatments to match durability. The DMLS process began with slicing software generating support structures tailored to each guide's geometry and orientation on the build platform, achieving a precision of 0.1 mm. These supports were critical to stabilize the part during printing, preventing warping under the high temperatures of the laser. After printing, supports were retained during the green stage to maintain structural integrity and minimize damage risks. Post-processing involved carefully removing supports using precision tools and manual machining to smooth uneven surfaces and ensure a flush fit against the mandibular surface. An optical surface profilometer verified the guides' geometric accuracy, confirming dimensional fidelity within 0.1 mm. Final surface refinement, including polishing, eliminated imperfections to meet surgical standards, ensuring the guides' biocompatibility and readiness for sterilization before intraoperative use.

Fig. 8 Cobalt chromium surgical guides

2.7. Surgical Producers using Metal Surgical Guides

Prior to surgery, the surgical guides were sterilized. The patient was in the supine posture, lying flat on his back. The surgical guides were precisely positioned on the mandible during the procedure with the help of virtual and preplanning surgical procedures.

Doctors performed surgery according to the guidelines after making submandibular incisions to expose the bone surface, placing the surgical guide on the exposed bone surface, and wrapping it around the mandibular angle. Further, fine drilling is performed using screw holes to create holes in the mandible to fix the surgical guides. After that, the edges of the mandibular lesions from both sides were removed along the surgical guides. Figure 7 (a) shows the patient's tumour location, and doctors are removing the tumour from the patient.

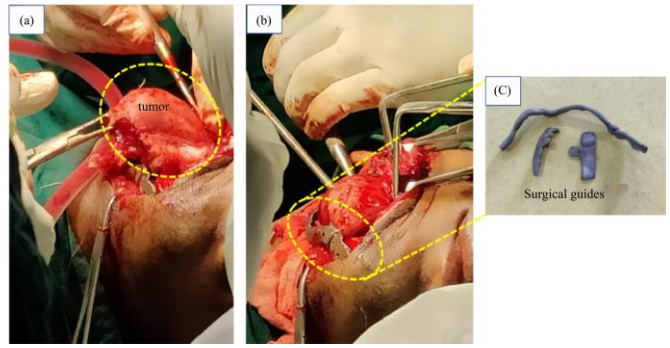

Fig. 9 (a) The surgical guides are placed inside the mandible, (b) The fixation of the surgical guides are placed based on preplanning surgery, and (c) AM metal surgical guides.

The realignment of edges is secured to the jaw with screws (Figure 7 (b)). The printed surgical guides are shown in Figure 7 (c). The guide was used to remove the front side of the right mandibular tumour in accordance with the preoperative plan, and the mandible condyle portion tumour was cut implicitly during the procedure. However, the lateral edge of the condyle was too short for the osteotomy guide to be inserted. A wire was used to fasten the mandible condyle neck to the grafted fibula's distal end. The occlusal relationship of the remaining teeth was then examined once the mandibular condyle reached the retruded contact point. After the surgery, the remaining dentition's occlusal relationship was normal, with any defects predominantly concentrated on the lateral portion of the right condyle. This was revealed by a maxillofacial CT examination, which also revealed that the postoperative effect of the mandible reconstruction was essentially the same as that of the preoperative design.

3. Results and Discussions

Virtual surgical planning and preplanning surgery significantly reduce overall surgical time by enabling precise anatomical assessment, accurate surgical guide placement, and efficient intraoperative decision-making. As previously mentioned, the AM metal surgical guides enhance the clinical outcome of fibular flap grafting for the restoration of mandibular deformities by having high osteotomy accuracy. Surgical guides improve precision and reduce intraoperative planning time. Table 1 presents a comparison of the surgical procedure time with and without the use of surgical guides. It can lower the duration of the procedure and the risk involved.

Having a nice facial aesthetic in addition to functional recovery is the aim of mandibular defect restoration. The clinical outcome of mandibular reconstruction can be affected by a number of key aspects, including the specific morphologies and complex movement forms, the types of lesions, and the location and degree of the defect [24]. While performing surgery on a tumour patient, mandibular distraction osteogenesis carries a high risk of postoperative consequences, including bone nonunion, infection, scarring, permanent tooth damage, tractor fall off, fracture accidents, damage to the mandibular alveolar nerve, and scarring [25]. Preoperative personalized planning is crucial to increase surgery efficacy and decrease postoperative complications because the severity of these congenital abnormalities varies greatly among patients.

Although advances in computerized structural modelling have given surgeons a platform to support customized surgical guide designs, actual surgery still presents challenges for application. However, a significant percentage of medical cases with remarkable results over a longer timeframe is still required to verify the long-term outcomes of the patients' recovery of facial form, occlusal relation, and joint movement. The outcomes demonstrated that the patient's surviving teeth had a normal occlusal relationship and that the actual reconstruction impact was mostly congruent with the preoperative design scheme.

Table 1. Estimated surgical procedure time with and without AM surgical guides

Surgical Step	With Surgical Guides	Without Surgical Guides
Patient positioning and anaesthesia	20–30 minutes	20–30 minutes
Submandibular incision and bone exposure	15–20 minutes	15–20 minutes
Placement and alignment of surgical guides	10–15 minutes	—
Manual marking and planning of resection	—	30–45 minutes
Drilling/fixation using a guide or freehand	15–20 minutes	20–30 minutes
Tumor resection	30–45 minutes	45–60 minutes
Realignment and fixation of mandible segments	20–30 minutes	30–40 minutes
Occlusal check and final adjustments	10–15 minutes	15–20 minutes
Total Estimated Surgical Time	2.0–2.5 hours	3.0–3.5 hours

4. Conclusion

The pre-surgical simulation also helps identify any necessary design adjustments, thereby improving the reliability and success rate of the surgical procedure. Simulating the surgical procedure in advance enables careful evaluation of anatomical constraints and aids in planning the optimal resection path. As a result, it supports effective tumor removal while minimizing the risk of damaging adjacent healthy tissues. This approach enhances surgical precision, reduces intraoperative decision-making time, and contributes to improved clinical outcomes. The physical strength and accuracy of three-dimensional printed surgical guides are sufficient to suit the clinical needs of challenging mandibular distraction osteogenesis. This procedure can drastically reduce the amount of time needed for surgery with the use of AM surgical guides. Our findings need to be confirmed by prospective investigations. We believe using the right AM method and materials can cut synthesis costs while meeting therapeutic needs. Developing surgical guides is difficult for an engineer, necessitating additional consideration during the implant design process. In this type of situation, the quality of the implant is always a matter of concern that must never be overlooked, even if the manufacturing process is longer. This investigation has the potential to verify the safety of the surgical guides that have been developed.

4.1. Future Scope of Work

Investigate biocompatible polymers and composites, such as Polylactic Acid (PLA) for prototyping, polyetheretherketone (PEEK) for durable guides, and carbon fiber reinforced composites for enhanced strength, to improve accessibility in resource-limited settings.

Ethical Approval

The article accurately and completely reflects the writers' research and analysis.

Data and Material Accessibility

Data accessibility is unrelated to this article because no new data were created or analyzed for this investigation.

Consent to Participate

All authors hereby confirm their participation in the publication of this article.

Consent to Publish

All authors hereby confirm the publication of this article.

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