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Review Article

UTILIZING 3D PRINTING TECHNOLOGY FOR ENHANCED PREOPERATIVE PLANNING IN ORTHOPEDIC SURGERY: A NARRATIVE REVIEW

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ABSTRACT
In orthopedic surgery, accuracy and careful preparation before surgery are essential for positive results. In this field, additive manufacturing, also called 3D printing technology, has become a game-changing instrument. It enables the creation of patient-specific anatomical models, custom surgical tools, and personalized implants, enhancing the accuracy and efficiency of surgical procedures. While the potential benefits are significant, the integration of 3D printing into routine practice and its long-term implications are still under exploration. This narrative review aims to systematically assess the current state of 3D printing technology in preoperative planning for orthopedic surgery, focusing on its applications, benefits, challenges, and the quality of the evidence supporting its use. The review highlights the diverse applications of 3D printing across various orthopedic procedures, including joint replacement, spine, and trauma surgeries. Studies indicate that 3D printing contributes to improved surgical planning, reduced operative times, and potentially better patient outcomes. However, challenges related to cost, accessibility, and the need for specialized training are noted. The review also discusses the quality of current research, emphasizing the need for more high-quality, long-term studies to better understand the technology's impact. As 3D printing technology continues to advance, it holds the promise of further revolutionizing orthopedic surgery. Future research should focus on long-term patient outcomes, cost-effectiveness, and the development of guidelines for its use. The potential for 3D bioprinting and the creation of biological implants also opens new avenues for personalized and regenerative medicine. Clinicians and policymakers must weigh 3D printing's revolutionary promise against its existing limitations. Research, training, and infrastructure are needed to maximize its benefits. As data increases, clinical standards and policies will be needed to standardize 3D printing in orthopedic preoperative planning for safety, efficacy, and equitable access.

Keywords: *3D Printing in Orthopedics, Preoperative Planning, Surgical Outcomes, Additive Manufacturing*
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INTRODUCTION
Orthopedic surgery, a field characterized by its complex procedures and the critical need for precise anatomical understanding, has continually sought innovations to improve surgical outcomes and patient care. The advent and integration of 3D printing technology into preoperative planning represents a significant leap forward in this endeavor. This technology, also known as additive manufacturing, allows for the creation of patient-specific anatomical models, custom surgical tools, and even personalized implants, all of which contribute to more accurate and efficient surgical procedures.

The concept of using 3D printing in medicine is not new; however, its application in orthopedics has seen a rapid expansion in recent years. Traditional preoperative planning relied heavily on 2D imaging techniques like CT scans, X-rays, and MRI, which provide valuable information but often fall short in conveying the complex three-dimensional nature of musculoskeletal anatomy. 3D printing technology addresses this limitation by converting these 2D images into tangible models that surgeons can hold, study, and even practice before the actual surgery [1].

These patient-specific models have proven particularly beneficial in complex cases, such as those involving anatomical deformities, intricate trauma, or revision surgeries where standard implants and tools may not suffice. By allowing surgeons to understand patient anatomy in three dimensions and plan accordingly, 3D printing has been shown to reduce operative time, reduce the risk of complications, and improve overall surgical outcomes.

Furthermore, the ability to print custom surgical instruments and implants tailored to the patient's unique anatomy has opened new frontiers in personalized medicine. This not only enhances the fit and integration of implants but also significantly reduces the need for intraoperative adjustments, leading to shorter and more efficient surgeries [2].

However, despite its promising benefits, the integration of 3D printing into routine orthopedic practice is not without challenges. Issues related to cost, accessibility, and the need for specialized training are among the factors that currently

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limit widespread adoption. Moreover, as with any rapidly evolving technology, there is an ongoing need for rigorous research to better understand the long-term outcomes and potential risks associated with its use.
This narrative review aims to address several important topics about the preoperative planning of orthopedic surgery about the use of 3D printing technology. First, it aims to understand how 3D printing improves the accuracy and efficiency of surgical procedures compared to traditional preoperative planning methods. Secondly, it explores the specific types of orthopedic procedures that most benefit from 3D printing, delving into the range and nature of applications across different surgeries. Thirdly, the review addresses the tangible benefits and potential challenges faced by surgeons and healthcare systems when adopting this technology. Lastly, it seeks to identify the quality of the current evidence supporting the use of 3D printing in orthopedics and to outline the future implications for clinical practice and patient care, including how it might evolve with ongoing technological advancements.

METHODOLOGY

The data was systematically gathered, assessed, and synthesized from the existing literature on the application of 3D printing technology in preoperative planning for orthopedic surgery, focusing on its impact, benefits, challenges, and future implications. A thorough search was carried out across several databases, including Google Scholar, PubMed, Scopus, and Web of Science. Keywords such as "3D printing in orthopedics," "preoperative planning," "additive manufacturing," "patient-specific models," and "custom surgical tools" were used in various combinations to ensure a wide coverage of relevant literature. Reference lists of identified articles were also checked for additional sources.
Only English-language articles were considered for review, as the selected databases primarily index English publications. The review focused on literature published between 2010 and 2023, reflecting the recent advancements and growing adoption of 3D printing technology in orthopedic surgery.
Important details were extracted from each chosen study, such as the author(s), publication year, study design, sample size, type of orthopedic treatment, specific application of 3D printing technology, primary conclusions, and highlighted benefits and challenges. Various study designs were considered, including randomized controlled trials (RCTs), cohort studies, case-control studies, case series, and narrative reviews, to ensure a broad range of evidence. Studies included had sample sizes ranging from small case series (e.g., fewer than 10 patients) to larger cohort studies (up to several hundred patients), providing a comprehensive look at the impact of 3D printing technology across different orthopedic applications.
Data was synthesized narratively to provide a comprehensive overview of the current state of 3D printing in preoperative planning for orthopedic surgery. The synthesis focused on the types of orthopedic procedures that benefited from 3D printing, the specific applications of the technology, the reported benefits and challenges, and the quality of evidence supporting its use.

PREOPERATIVE PLANNING USING 3D PRINTING IN ORTHOPEDICS

Preoperative planning is a critical phase in orthopedic surgery where the surgeon strategizes the procedural steps and predicts the challenges they might encounter. The advent of 3D printing technology has revolutionized this process, offering a more refined, patient-specific approach that significantly enhances the surgical outcome.
Adding material layer by layer to a computer file to create three-dimensional items is known as additive manufacturing or 3D printing. In orthopedics, this technology is used to create accurate models of patient anatomy based on their CT or MRI scans. These models enable surgeons to visualize and interact with the patient's anatomy in a way that was not possible with traditional two-dimensional imaging techniques [3].
One of the primary advantages of using 3D printing in preoperative planning is the ability to understand complex anatomical structures in a tangible form. This is particularly beneficial in cases involving intricate structures or deformities where a deep understanding of spatial relationships is crucial. Surgeons can physically hold the model, rotate it, and even simulate the surgical procedure, which can increase their confidence and reduce the likelihood of intraoperative surprises.
Furthermore, implants and tools customized for each patient can be produced through 3D printing. By exactly fitting the patient's unique anatomy, these specially manufactured instruments can shorten the duration of the procedure, lower the risk of infection, and enhance the fit and lifetime of implants. For instance, in joint replacement surgeries, custom jigs and guides can ensure more accurate placement of the prosthetics, leading to better functional outcomes and increased patient satisfaction [4].
In complex trauma cases, 3D printed models can help in understanding the fracture patterns and planning the reduction and fixation strategies. This can be particularly advantageous in pelvic and acetabular fractures, where the anatomy is complex, and traditional approaches can be challenging [5].
However, despite its numerous benefits, the adoption of 3D printing in routine clinical practice is not without challenges. Issues such as the cost of the technology, the need for specialized training, and concerns regarding the sterilization of printed models are some of the hurdles that need to be addressed. Additionally, there's a need for more high-quality

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research to determine the long-term outcomes and cost-effectiveness of this technology in various orthopedic procedures.

SPINE SURGERY

Spine surgery is a complex field that demands precise planning and execution due to the intricate anatomy and the critical functions of the spinal cord and nerves. 3D modeling, facilitated by advances in 3D printing technology, has emerged as a powerful tool for surgeons in preoperative planning, patient education, and even intraoperative guidance.

3D modeling involves creating a three-dimensional representation of the spine using imaging data, typically from CT or MRI scans. This model can then be used to understand the pathology, plan the surgical approach, and even create custom surgical instruments or implants. The accuracy and tactile feedback provided by these models offer a significant advantage over traditional two-dimensional imaging techniques.

One of the primary applications of 3D modeling in spine surgery is in the management of complex deformities and trauma. In cases of scoliosis or severe spinal deformities, 3D models allow for a better understanding of the anatomy and can help in planning corrective measures with greater precision [6]. Surgeons can simulate different strategies on the model to determine the most effective approach, reducing the risk of intraoperative complications and improving postoperative outcomes.

In spinal trauma, particularly in cases involving the cervical spine, 3D models can be invaluable in understanding fracture patterns and planning fixation strategies. The models provide a clear view of the fracture fragments and their relationship to critical structures, which is crucial for successful reconstruction.

3D modeling is also gaining traction in the design of custom implants and surgical instruments. For example, in spinal fusion surgeries, patient-specific interbody cages created using 3D printing can match the patient's anatomy perfectly, leading to better stability and fusion rates. Similarly, custom drill guides can ensure the accurate placement of pedicle screws, which is crucial for the stability of the construct [7].

However, the integration of 3D modeling into clinical practice is not without challenges. Issues such as the cost of 3D printers, the time required to create the models, and the need for specialized training can be significant barriers. Additionally, there is a need for more robust data on the long-term outcomes of surgeries planned with the aid of 3D models to fully understand their benefits and limitations.

HIP AND PELVIC SURGERY

Hip and pelvic surgeries are intricate procedures that require precise anatomical understanding and meticulous planning due to the complex structure of the pelvic region and the crucial role of the hip joint in weight-bearing and mobility. 3D modeling, empowered by advancements in 3D printing technology, has become a transformative tool in this domain, offering enhanced preoperative planning, patient-specific implants, and improved surgical outcomes.

1. Enhanced Preoperative Planning

3D models provide a tangible, accurate representation of the patient's anatomy, allowing surgeons to visualize and assess complex hip and pelvic pathologies in a way that 2D images cannot. This is particularly beneficial in cases involving congenital deformities, severe trauma, or revision surgeries where standard approaches and implants may not suffice. Surgeons can manipulate these models to better understand the spatial relationships and to plan osteotomies and implant placements with greater precision.

2. Custom Implants and Surgical Tools

In hip arthroplasty, patient-specific implants designed through 3D modeling have shown potential to improve the fit and longevity of the implants. Similarly, in pelvic reconstructions, particularly after tumor resections or severe fractures, 3D-printed pelvic prostheses can be tailored to the patient's specific anatomy, potentially leading to better functional outcomes and lower rates of complications [8]. Custom surgical guides and tools can also be created, ensuring accurate implant placement and reducing operative time.

3. Improved Patient Communication and Education

3D models can be an invaluable tool for explaining complex surgical procedures to patients. By visualizing their anatomy and the planned interventions, patients can have a better understanding of their condition and the surgery, leading to improved satisfaction and potentially better compliance with pre-and post-operative instructions [9].

4. Training and Simulation

The field of orthopedic education can also benefit from 3D modeling. Trainees can practice on patient-specific models, gaining a deeper understanding of various pathologies and surgical techniques before stepping into the operating room. This can enhance their skills and confidence, ultimately leading to better patient care. While the benefits of 3D modeling in hip and pelvic surgery are clear, there are challenges and limitations to consider. The cost and time associated with producing high-quality 3D models can be significant, and there is a learning curve associated with integrating this technology into surgical practice.

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Additionally, long-term studies are needed to fully understand the impact of 3D modeling and patient-specific implants on patient outcomes.

SURGERY AROUND THE KNEE

3D printing technology has increasingly become a pivotal tool in orthopedic surgeries around the knee, such as Total Knee Arthroplasty (TKA), osteotomies, and cruciate ligament repairs. Traditional methods like preoperative templating on plain radiography, while useful, have limitations in predicting component sizes and postoperative limb alignment with the precision that 3D modeling offers.

3D printed patient-specific cutting guides, or PSCGs, have shown a significant increase in knee alignment accuracy, a reduction in surgery time, and a decrease in intraoperative blood loss in total knee arthroplasty (TKI). By facilitating customized intraoperative bone cutting for the femoral and tibial components, these guides guarantee ideal implant location and alignment, which is essential for the procedure's long-term survival [10].

The role of 3D printing extends beyond TKA. In anterior cruciate ligament (ACL) reconstruction, the technology aids in the precise positioning of femoral and tibial tunnels. Anatomical ACL reconstruction is vital for restoring the function of the native ACL, and 3D printing assists in identifying patient-specific anatomical landmarks to guide accurate tunnel creation [11]. This leads to improved knee stability and function post-surgery.

Another use for 3D printing is in knee osteotomies, specifically in medial opening wedge high tibial osteotomy (OWHTO), a treatment for osteoarthritis of the medial compartment. Traditional preoperative planning often results in under-correction, but 3D printing offers a more nuanced multiplanar assessment of the proximal tibia, enabling a more accurate correction [12]. Customized 3D-printed wedges and surgical guides contribute to successful outcomes with fewer complications.

Despite these advancements, it is essential to recognize the limitations and challenges of 3D printing in clinical practice, including costs, the need for technical expertise, and the necessity for further research to establish long-term outcomes.

FOOT AND ANKLE SURGERY

3D printing technology has become a vital tool in the field of foot and ankle surgery, where accuracy meets complexity, giving doctors an unmatched advantage in treating complex injuries and deformities. The ability to create detailed 3D printed models from patient imaging data is revolutionizing the preoperative planning, execution, and outcome of surgeries in this challenging field.

The use of 3D models for preoperative planning and surgical simulation has been shown to significantly aid in the correction of foot and ankle deformities. For instance, Jastifer and Gustafson [13] highlighted the successful use of 3D printing in treating the malunion of the fibula with posterior translation relative to the talus. The technology provided them with a tangible representation of the deformity, aiding in meticulous planning and execution of the corrective surgery. Similarly, the efficacy of 3D printed models in improving surgical outcomes for patients with hallux valgus deformity allows for a more precise osteotomy and better postoperative foot function.

3D printing technology's forte lies in its ability to create patient-specific instruments (PSIs) and cutting guides, which have been reported to significantly improve surgical accuracy and safety. For instance, a clinical study by Xu et al. [14] on moderate and severe hallux valgus osteotomy revealed that the use of 3D-printed navigation templates resulted in higher AOFAS scores and lesser metatarsal shortening compared to traditional methods. This highlights the potential of 3D modeling not just in planning but also in guiding the surgical procedure itself.

In more complex scenarios, such as tibial plafond fractures and calcaneal fractures, 3D models have proven to be invaluable. A comparative study by Zheng et al. [15] on calcaneal fractures revealed that 3D-assisted surgery shortened operation duration, decreased blood loss, and reduced intraoperative fluoroscopy exposure, underscoring the multifaceted benefits of 3D printing in surgical precision and patient safety.

3D printing is also making its mark in arthroscopic procedures and minimally invasive surgeries (MIS). The use of 3D printed models in MIS of calcaneal fractures shows that it improved the accuracy of screw placement and the overall shape of the reduced calcaneus [16]. This technology is proving to be a game-changer in surgeries where precision is paramount and the margin for error is minimal.

A set of instances demonstrating the therapeutic uses of personalized 3D-printed implants in intricate lower limb reconstructions was given by Kadakia et al. [17]. 3D-printed implants that were customized to the anatomy of the patient offered structural support and fit the specific needs of each case, demonstrating the personalized nature of future orthopedic procedures. These implants ranged from enhancing tibiotalocalcaneal arthrodesis to total talus arthroplasty.

DISCUSSION

The integration of 3D printing technology in orthopedic surgery, particularly in procedures around the knee, spine, hip, pelvis, foot, and ankle, has opened up new vistas for surgical precision and personalized patient care. The ability to create patient-specific anatomical models, custom surgical tools, and customized implants has proven to be a game-changer, particularly in complex and intricate cases.

Orthopedic surgery appears to have a promising future with 3D printing as technology advances. With advancements in materials and printing technology, the production of 3D models and custom tools is expected to become more cost-effective and accessible. This could lead to wider adoption and integration of 3D printing in routine clinical practice, offering more patients the benefits of personalized and precise surgical care.

Furthermore, the potential for 3D bioprinting – printing with cells and biological materials – opens up new possibilities for regenerative medicine. In the future, we might see the printing of biological implants that not only match the patient's anatomy but also integrate seamlessly with their body, promoting natural healing and regeneration.

However, for these potentials to be fully realized, ongoing research and clinical trials are essential to better understand the long-term outcomes, risks, and cost-effectiveness of 3D printing in various orthopedic procedures. Collaboration between engineers, surgeons, and regulatory bodies is also crucial to ensure the technology's safe and effective use.

CONCLUSION

3D printing technology represents a transformative advance in preoperative planning for orthopedic surgery. By providing surgeons with a deeper and more intuitive understanding of patient anatomy, facilitating the creation of personalized surgical tools and implants, and potentially improving surgical outcomes, it holds great promise for the future of orthopedic care. As the technology continues to evolve and become more accessible, it is expected to become an increasingly integral part of the orthopedic surgical landscape.

Limitations

The reviewed research on 3D printing technology in preoperative planning for orthopedic surgery revealed several limitations in the quality and consistency of the studies. Many of the articles included small sample sizes or narrative reviews, which limit the ability to generalize findings and provide statistically robust conclusions. Furthermore, there was a noticeable lack of randomized controlled trials (RCTs), considered the gold standard in clinical research, reducing the strength of the evidence supporting the technology's long-term effectiveness. Another limitation was the inconsistency in outcome reporting across studies, making it difficult to compare results or establish standardized measures of success. Additionally, factors such as cost-effectiveness and the accessibility of 3D printing technology, particularly in resource-limited settings, were underexplored, as were the training requirements necessary for healthcare professionals to implement the technology effectively.

Future Research

Future research should focus on conducting larger, high-quality clinical trials, particularly RCTs, to provide more definitive evidence of 3D printing's benefits in orthopedic surgery. Standardizing outcome measures will also be critical to allow for better comparison across studies. Additionally, long-term studies are needed to assess the cost-effectiveness and patient outcomes associated with 3D printing. Research should also explore the development of training programs and protocols to help integrate 3D printing more seamlessly into clinical practice. Lastly, further investigation into bioprinting and new materials could unlock even more personalized and regenerative solutions for orthopedic patients.

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List of abbreviations

3D: Three-Dimensional
TKA: Total Knee Arthroplasty
MRI: Magnetic Resonance Imaging
CT: Computed Tomography
PSCGs: Patient-Specific Cutting Guides
ACL: Anterior Cruciate Ligament
OWHTO: Medial Opening Wedge High Tibial Osteotomy
MIS: Minimally Invasive Surgery
AOFAS: American Orthopedic Foot and Ankle Society Score
TTC: Tibiotalocalcaneal

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Conflict of interest

The authors have no competing interests to declare.

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