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The expanding role of additive manufacturing in orthopaedic traumatology

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Abstract The 2023 Orthopaedic Trauma Association's Basic Science Focus Forum featured a symposium on additive manufacturing (AM) in orthopaedics. Three experts presented on various aspects of AM: Dr. Malcolm DeBaun discussed custom 3D-printed implants for segmental bone loss, Dr. Samir Mehta explored 3D printing in education and surgical planning, and Dr. Guha Manogharan addressed challenges and opportunities in AM and hybrid manufacturing. The symposium highlighted AM's significant impact across clinical, educational, and industrial applications in orthopaedic trauma.

Keywords: additive manufacturing, fracture, implant design, biomechanics

1. Introduction

At the 2023 annual meeting of the Orthopaedic Trauma Association, the Basic Science Focus Forum hosted a symposium that discussed the role of additive manufacturing (AM). Invited speakers provided insight and context to current developments in trauma implant design, AM-based education, and future applications of 3D printing. The first talk, entitled "Custom 3D Printed Implants for Segmental Bone Loss," was presented by Dr. Malcolm DeBaun. "3D Printing in Orthopaedic Trauma Education and Surgical Planning" was presented by Dr. Samir Mehta, and "What is all the fuss about Additive Manufacturing (AM) and Hybrid Manufacturing? Challenges and Opportunities to address Critical Orthopaedic Needs" was presented by Dr. Guha Manogharan. This symposium was designed to emphasize the vast impact of AM devices in the clinic, classroom, and industry sector. The work of each presenter is summarized in the following.

2. Custom 3D Printed Implants for Segmental Bone Loss

Segmental bone loss after trauma or bone resection provides unique challenges to both the patient and the surgeon. Traditional limb salvage management options include bone transport, induced membrane technique, and vascularized fibula autograft transplantation. Custom three-dimensional (3D)–printed implants have recently provided a unique single-stage solution for segmental bone loss that facilitates early weight bearing without donor morbidity or a prolonged, labor-intensive treatment course.[1]

There are several distinct advantages to 3D-printed implants for managing critical bone loss after trauma. First, there is significant flexibility in the digital design and manufacturing process for customization to meet patient and injury-specific needs. The custom implant can also be coupled with prefabricated implants or intended to be merged with bone graft. Second, these implants are typically constructed with porosity and macrostructure (eg, gyroid), enabling osseointegration and preventing stress shielding.[2,3] Third, these implants can be made structural to provide immediate length stability and weight bearing.

Although regenerative solutions remain the mainstay of segmental bone loss management after trauma, certain patient-specific or injury-specific factors may be preclusive. Custom 3D-printed structural implants have emerged as a reasonable alternative option for treating aseptic critical bone defects definitively. Further study is required to refine indications and establish best practices.

To reinforce these principles, a case study was presented: A 65-year-old healthy man presented with a type 3B open tibia fracture with segmental bone loss after a motorcycle crash. His injury was associated with an ipsilateral tibial plateau fracture and a completely devitalized intercalary diaphyseal segment (Fig. 1A). After initial temporization with debridement and external fixation, the patient underwent open reduction and plate fixation with cement spacer placement and soft-tissue coverage. While awaiting the definitive healing of his free flap, a

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Figure 1. A 65-year-old healthy man presented with a type 3B open tibia fracture with segmental bone loss after a motorcycle crash. His injury was associated with an ipsilateral tibial plateau fracture and a completely devitalized intercalary diaphyseal segment (A). At a recent follow-up, over 1 year after definitive surgery, the patient was ambulating pain-free without assisted devices and evidenced osseointegration was seen on the radiographs (B).

custom 3D-printed titanium strut was designed and fabricated. Ultimately, resection of the devitalized segment and removal of the cement spacers and plates were performed. During the same surgery, the definitive titanium strut was implanted and coupled to a trauma nail to span the segmental defect with the initiation of weight bearing. At a recent follow-up, over 1 year after definitive surgery, the patient was ambulating pain-free without assisted devices and evidenced osseointegration was seen on the radiographs (Fig. 1B). The patient provided written consent to present his case.

3. 3D Printing in Orthopaedic Trauma Education and Surgical Planning

The field of medicine is undergoing a transformative shift with the advent of AM. This technology is particularly revolutionizing the practice of orthopaedics, where AM models of patient anatomy are increasingly used for various purposes, including preoperative planning, intraoperative referencing, and training in surgical skills. Orthopaedic applications of AM extend to areas such as fracture fixation; implant selection; and the creation of patient-specific instrumentation, orthoses, and prosthetics.

In our study, conducted with institutional review board approval in accordance with the Declaration of the World Medical Association, we focused on evaluating the impact of tactile learning on the performance of orthopaedic residents performing fracture fixation surgeries. The study involved 12 orthopaedic residents, who performed 17 matched pairs of surgeries. Experience levels ranged from postgraduate year (PGY) 2 to PGY 5. The surgeries covered various anatomical locations and complexities, providing a comprehensive assessment of the effectiveness of AM models.

To quantify changes in learning, we used the Ottawa scoring system, a validated assessment tool using a Likert scale,[4] to objectively measure surgical competency. We hypothesized that preoperative examination of AM models by orthopaedic residents would significantly enhance their competence in the operating room and positively affect clinical outcomes.

The AM model group, which had the opportunity to interact with AM fracture models 24 hours before surgery (Fig. 2), exhibited a significant improvement in Ottawa scores, indicating enhanced surgical competency. This improvement was particularly notable in categories such as visuospatial skills, preprocedure planning, case preparation, and efficiency. The control group, which followed the standard treatment protocol without AM models, showed nonsignificant changes in Ottawa scores between the first and second surgeries. Clinical outcomes also demonstrated the benefits of AM model training, with the AM model group showing greater improvements in operating room time, fluoroscopy time, and patient-reported physical function compared with the control group.

This study explored the residents' preferred learning styles using the Visual, Auditory, Read/Write, and Kinesthetic (VARK) learning styles inventories, revealing that a significant portion of the residents (42%) preferred kinesthetic learning. The findings suggest that personalized learning approaches, such as the tactile learning provided by AM models, could be crucial in improving orthopaedic resident education.

We acknowledge this study's limitations, including its single-institution setting and small sample size. Despite this, the results demonstrate the potential of AM models to enhance surgical competency and clinical outcomes in orthopaedics. These findings highlight the need for further research to explore the long-term impact of AM model training and the feasibility of

Figure 2. A frontal plane view of a distal fibula and tibia fracture from CT imaging (left) and the resulting additively manufactured model that was used for training before surgery.

incorporating this technology regularly into orthopaedic education.

In conclusion, this study provided fresh insights and quantitative data that provide further evidence of the transformative role of additive manufacturing in orthopaedics. We believe that the improved surgical skills, decision making, and overall clinical outcomes could benefit surgeons of all levels of experience—not just residents. As technology continues to advance, the integration of AM models into medical education and practice may become increasingly commonplace, which will foster more effective and personalized training in surgical disciplines.

4. What Is All the Fuss About Additive Manufacturing and Hybrid Manufacturing? Challenges and Opportunities to Address Critical Orthopaedic Needs

The role of AM continues to evolve, and new techniques are being developed to blend AM and traditional manufacturing methods, known as hybrid AM techniques. This approach has been used successfully in industrial, aerospace, and defense applications, but the primary focus here is to explore the transformative impact of AM in medical applications, specifically for orthopaedic applications.[5]

In the evolving landscape of orthopaedics, the integration of digitally driven design and manufacturing ushers in a new era, redefining how critical clinical challenges are addressed. In particular, there is widespread interest in developing biomimetic designs, which are only facilitated by AM. Biomimetic designs offer unparalleled control over tailoring mechanical properties, thereby addressing the specific needs of orthopaedic applications.[6–9] Unique lattice architectures within these designs can be designed to encourage bone ingrowth and vascularization. In addition, the greater effective surface area of these biomimetic designs can be leveraged for biofunctionalization and infection prevention, which are critical for implant success.[10]

It is important to understand the relationships between AM design features, biomaterials, and biology. Within this space, we need to explore the morphological and topological responses of AM biomimetic porous biomaterials. There is also a need to focus on understanding the structure–function relationships of these biomaterials and their success in mimicking diverse biomechanical properties of human bone.

A significant advantage of 3D-printed implants is their structural composition, allowing for the tuning of immediate length, stability, and weight-bearing capabilities.[11–13] This feature may be particularly helpful in facilitating the restoration of functionality and mobility in patients with segmental bone loss. The structural integrity of these implants can be tuned to allow patients to engage in early weight-bearing activities, which may improve healing responses.

The design of 3D-printed implants incorporates essential features such as porosity and macrostructure, often characterized by intricate geometries such as gyroid or primitive patterns that allow for fluids and nutrients to flow through the scaffold (Fig. 3). This design strategy may be pivotal in fostering osseointegration because it improves implant integration with the surrounding bone tissue. Specifically, this design features a thoughtful macrostructure that helps prevent stress shielding, a phenomenon that can compromise the long-term success of orthopaedic implants.

While regenerative solutions remain integral in the management of segmental bone loss, certain patient-specific or injury-related factors may limit the applicability of these approaches. In such scenarios, custom 3D-printed structural implants emerge as a viable and reasonable alternative for definitively treating aseptic critical bone defects. However, further studies are warranted to refine the indications for using 3D-printed implants in these cases and to establish best practices for their implementation. Finally, future directions in multimaterial additive manufacturing, specifically on multimaterial laser powder bed fusion, were discussed that provide unprecedented opportunity to concurrently design and assign multiple materials (eg, bioactive materials such as zinc or magnesium with structural materials such as steel or titanium).

In conclusion, we have explored some of the synergies between AM and traditional manufacturing methods, which can be exemplified through hybrid AM. The transformative potential of AM in the orthopaedic domain remains unknown. Our work not only addresses challenges but also showcases the role of AM in improving manufacturing processes and advancing medical

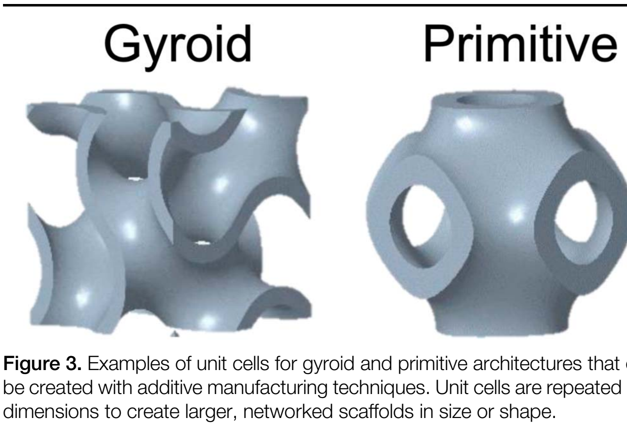

Figure 3. Examples of unit cells for gyroid and primitive architectures that can be created with additive manufacturing techniques. Unit cells are repeated in 3 dimensions to create larger, networked scaffolds in size or shape.

innovation. The future of AM implants is bright, as AM technologies are reshaping industries and revolutionizing health care, paving the way for a future where precision, efficiency, and customization converge seamlessly.

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