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3D PRINTING IN SURGERY AND MEDICINE

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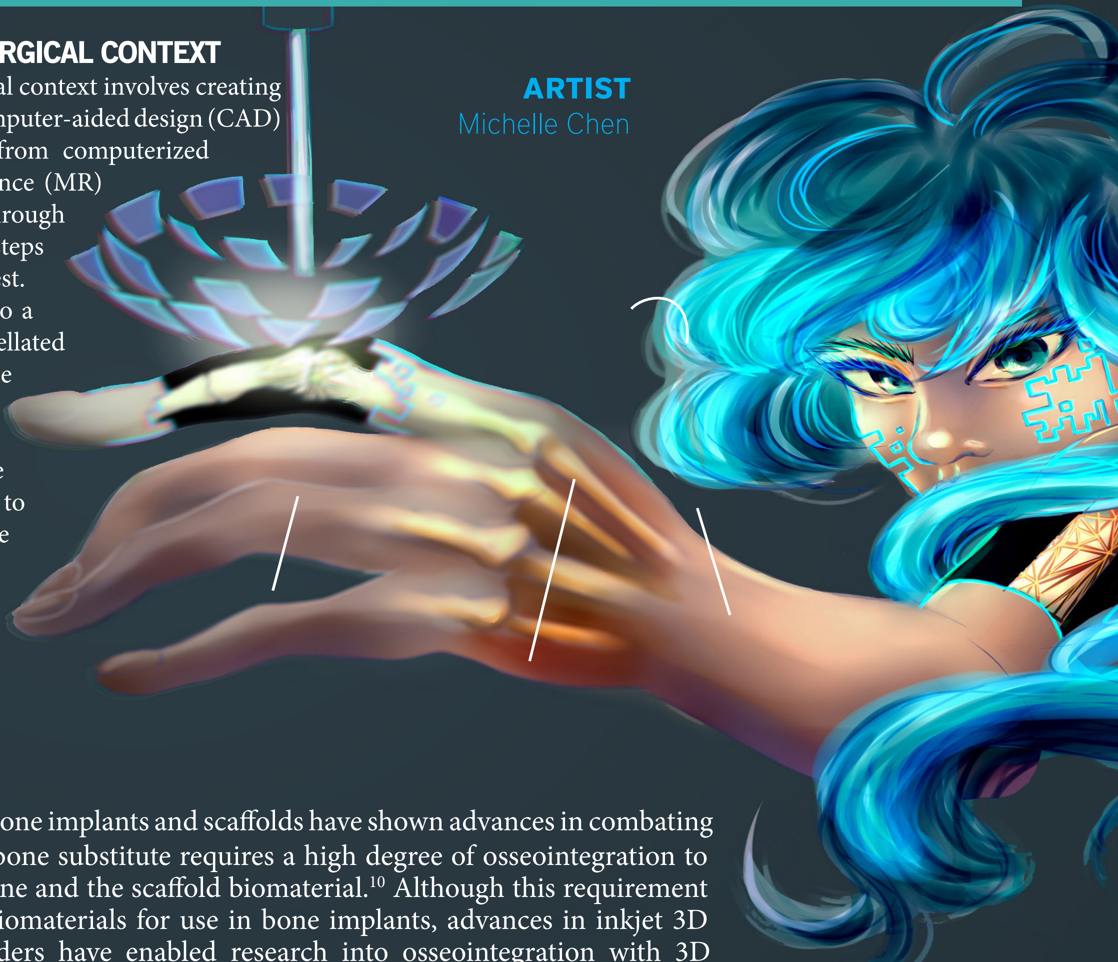
INTRODUCTION

Three-dimensional (3D) printing involves the creation of a 3D product through combining and depositing materials (i.e. plastic, metals, and ceramics) in layers.[1] Since the first patent was made by Charles Hull in 1984, advances in 3D printing technology have allowed it to be utilized in a variety of fields, including engineering and medicine.[2] Specifically, 3D printing technology has been useful in refining surgical techniques. 3D-printed anatomical models, surgical implants, and prosthetic limbs have proven to be beneficial in daily medical practice. Organ resection, reconstruction surgeries, reparative procedures, and organ transplantations have also been improved through this technology.[1,2,3]



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3D PRINTING METHODS IN A SURGICAL CONTEXT

The first step in 3D printing in a surgical context involves creating the 3D model itself, usually through computer-aided design (CAD) software or the conversion of data from computerized tomography (CT) or magnetic resonance (MR) scans.[3] Next, the images are set through post-processing and segmentation steps to extract anatomical regions of interest. These regions are then transcribed into a computerized model with which tessellated triangles are used to approximate the contours of the model.[4] This file can then be used by CAD software for further processing to improve the model's design, before being sent to the printer for producing a tangible 3D object.[3] The quality of the model is highly dependent on the quality of the original scans, with higher-resolution models scans producing higher-quality models.[3]

A NEW AGE FOR IMPLANTS

Research surrounding 3D-printed bone implants and scaffolds have shown advances in combating osseointegration.[9,10] Any potential bone substitute requires a high degree of osseointegration to facilitate the bond between new bone and the scaffold biomaterial.[10] Although this requirement has limited the available pool of biomaterials for use in bone implants, advances in inkjet 3D printing with titanium alloy powders have enabled research into osseointegration with 3D modeled structures.[9]

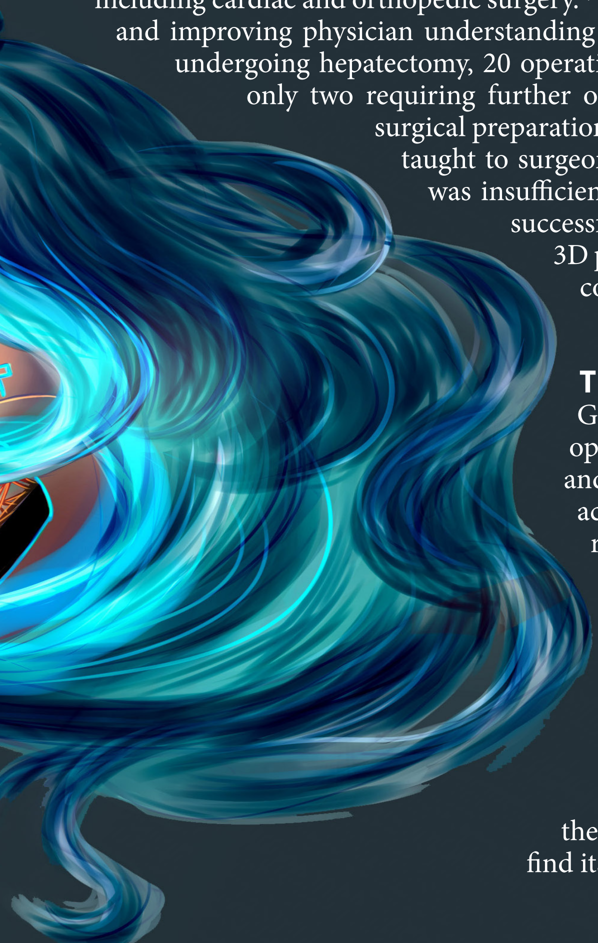
Beyond bone graft physiology, it is important to consider the functionality and survival of bone grafts post-implantation. All bone implants must minimize the impact of Wolff's Law: under physical stress, bone is deposited in areas where stress occurs the most and is removed where it occurs the least.[11] Consequently, any differences between the stress-bearing properties of the implant and surrounding bone tissue may result in long-term bone loss. Therefore, while bone graft integration is critical in promoting bone regrowth, it is also important to consider the load-bearing and stress-shielding mechanical properties as well as orientation of the graft in question.[12, 13]

To date, clinical applications of 3D-printed implants are few and far between, with most surgeons in this field applying bone tissue models to preoperational planning and surgical training.[11] However, studies utilizing 3D-printed scaffolds for bone regeneration seem promising, showing evidence that cellular proliferation and bone matrix formation are supported by these bone scaffolds.[12] Yet, with multiple methods to create 3D-printed tissue scaffolds that maximize osseointegration, more research is still required to generate reliable tissue scaffolds that facilitate bone regrowth while avoiding host rejections.[10,14,15,16]

MOVING TOWARDS IMPROVING SURGICAL PREPARATION

To better understand the extent of a disease in a patient prior to surgery, surgeons will rely on two-dimensional (2D) images obtained from X-rays, CT scans, or MRI scans.[4] However, 2D depictions may differ from what the surgeon actually encounters during an operation.5 This process intrinsically requires a high degree of visualization on the surgeon's part, which may be difficult for inexperienced surgeons.[4] Furthermore, a surgeon's understanding of a patient's anatomy may be complicated by variation or changes in shape due to disease progression.[5] While 3D renderings of radiography, CT, and MRI scans have been developed to better visualize complex pathologies, they lack tangibility.[4,5] These problems have prompted the use of 3D printing technology in pre-operational settings. Patient-specific anatomical models provide a tangible structure to manipulate —as opposed to 2D and 3D renderings of images —while maintaining accuracy.[5]

The introduction of 3D-printed anatomical models has markedly improved surgical preparation. For instance, they can be used by surgeons to perform "trial runs" for surgeries, allowing surgeons to predict potential technical challenges due to anatomical variations.[2,5] 3D-printed anatomical models have been used to prepare for surgeries in many disciplines, including cardiac and orthopedic surgery.[6,7] In these settings, researchers report that the models had been useful in planning and improving physician understanding of surgical procedures.[6,7] Additionally, a study showed that out of 22 patients undergoing hepatectomy, 20 operations were successful the first time with the help of 3D model preparation with only two requiring further open surgery.[3] There are limitations to the use of 3D printing technology for surgical preparation. Firstly, utilizing this technology necessitates specific skills that are not typically taught to surgeons.[8] Furthermore, it has been reported that the accuracy of 3D-printed models was insufficient in more precise surgeries, as certain anatomical structures are too fine to be successfully replicated.[3] Another concern among researchers is the cost of implementing 3D printing technology; however, with the increasing accessibility and the decreasing cost of 3D printing, this concern will likely diminish over time.[3,8]



THE FUTURE OF 3D PRINTING IN SURGERY

Given the successes of 3D printing in many aspects of surgery, there is much opportunity for growth. The money and time needed to print 3D models, implants, and prostheses are likely to decrease in comingyears, improving the clinical accessibility of this technology.[5] Furthermore, as research advances, a wider range of materials will permit better simulation of realistic tissues; surgeons will increasingly have access to better practice specimens, and consequently better surgical outcomes will be produced.[17]

Despite recent advancements in 3D printing technology, regulations for its use in surgery are virtually nonexistent. Currently, there are no formal protocols for using surgical 3D printing that can ensure a high degree of quality control. Such regulations, if implemented, must ensure that only the highest quality implants are used during surgery.[18] The adoption of these protocols is therefore the key to increasing surgeons' trust in this technology, so that one day it may truly find its place in the surgical toolbox.

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1. Ventola CL. Medical applications for 3D printing: Current and projected uses. *P T.* 2014;39(10):704-711. Available from: https://www.ncbi.nlm.nih.gov/pubmed/25336867 [cited 2019 Nov 6].
2. Shilo D, Emodi O, Blanc O, Noy D, Rachmiel A. Printing the future – Updates in 3D printing for surgical applications. *Rambam Maimonides Med J.* 2018;9(3):e0020. Available from: doi:10.5041/RMMJ.10343.
3. Li C, Cheung TF, Fan VC, Sin KM, Wong CWY, Leung GKK. Applications of three-dimensional printing in surgery. *Surg Innov.* 2017;24(1):82-8. Available from: doi:10.1177/1553350616681889.
4. Tack P, Victor J, Gemmel P, Annemans L. 3D-printing techniques in a medical setting: A systematic literature review. *Biomed Eng Online.* 2016;15:115. Available from: doi:10.1186/s12938-016-0236-4.
5. Pugliese L, Marconi S, Negrello E, Mauri V, Peri A, Gallo V, et al. The clinical use of 3D printing in surgery. *Updates Surg.* 2018;70(3):381-8. Available from: doi:10.1007/s13304-018-0586-5.
6. Schmauss D, Gerber N, Sodian R. Three-dimensional printing of models for surgical planning in patients with primary cardiac tumors. *J Thorac Cardiovasc Surg.* 2013;145(5):1407-8. Available from: doi:10.1016/j.jtcvs.2012.12.030.
7. Tam MD, Laycock SD, Bell D, Chojnowski A. 3-D printout of a DICOM file to aid surgical planning in a 6 year old patient with a large scapular osteochondroma complicating congenital diaphyseal aclasia. *J Radiol Case Rep.* 2012;6(1):31-7. Available from: doi:10.3941/jrcr.v6i1.889.
8. Martelli N, Serrano C, van den Brink H, Pineau J, Prognon P, Borget I, et al. Advantages and disadvantages of 3-dimensional printing in surgery: A systematic review. *Surgery.* 2016;159(6):1485-500. Available from: doi:10.1016/j.surg.2015.12.017.
9. Popov VV, Muller-Kamskii G, Kovalevsky A, Dzhenzhera G, Strokin E, Kolomiets A, et al. Design and 3D-printing of titanium bone implants: Brief review of approach and clinical cases. *Biomed Eng Lett.* 2018;8(4):337-44. Available from: doi:10.1007/s13534-018-0080-5.
10. Martinez-Marquez D, Mirnajafizadeh A, Carty CP, Steward RA. Application of quality by design for 3D-printed bone prostheses and scaffolds. *Plon.* 2018;13(4):e0195291. Available from: doi:10.1371/journal.pone.0195291.
11. Salter RB. Textbook of disorders and injuries of the musculoskeletal system. Baltimore: Williams & Wilkins; 1970.
12. Van Oosterwyck H, Duyck J, Vander Sloten J, Van der Perre G, De Coomans M, Lieven S, et al. The influence of bone mechanical properties and implant fixation upon bone loading around oral implants. *Clin Oral Implants Res.* 1998;9(6):407-18. Available from: doi:10.1034/j.1600-0501.1996.090606.x.
13. Oppenheimer AJ, Tong L, Buchman SR. Craniofacial bone grafting: Wolff's law revisited. *Craniomaxillofac Trauma Reconstr.* 2008;1(1):49-61. Available from: doi:10.1055/s-0028-1098963.
14. Tellisi N, Ashammakhi NA, Billi F, Kaarela O. Three dimensional printed bone implants in the clinic. *J Craniofac Surg.* 2018;29(8):2363-7 Available from: doi:10.1097/SCS.0000000000004829.
15. Helguero CG, Mustahsan VM, Parmar S, Pentyala S, Pfail JL, Kao I, Komatsu DE, Pentyala S. Biomechanical properties of 3D-printed bone scaffolds are improved by treatment with CRFP. *J Orthop Surg Res.* 2017;12(1):195. Available from: doi:10.1186/s13018-017-0700-2.
16. Bose S, Vahabzadeh S, Bandyopadhyay A. Bone tissue engineering using 3D printing. *Mater Today.* 2013;16(12):496-504. Available from: doi:10.1016/j.mattod.2013.11.017.
17. Ganguli A, Pagan-Diaz GJ, Grant L, Cvetkovic C, Bramlet M, Vozenilek J, et al. 3D printing for preoperative planning and surgical training: A review. *Biomed Microdevices.* 2018;20(3):65. Available from: doi:10.1007/s10544-018-0301-9.
18. Kwok JKS, Lau WHL, Zhao ZR, Yu PSY, Ho JYK, Chow SCY, et al. Multi-dimensional printing in thoracic surgery: Current and future applications. *J Thorac Dis.* 2018;10(Suppl 6):S756-63. Available from: doi:10.21037/jtd.2018.02.91.